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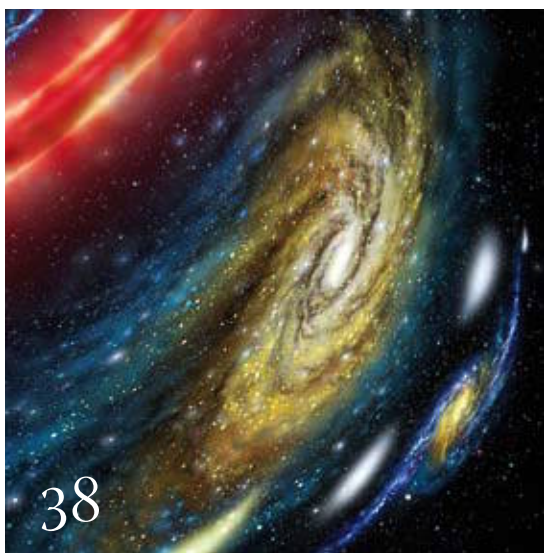

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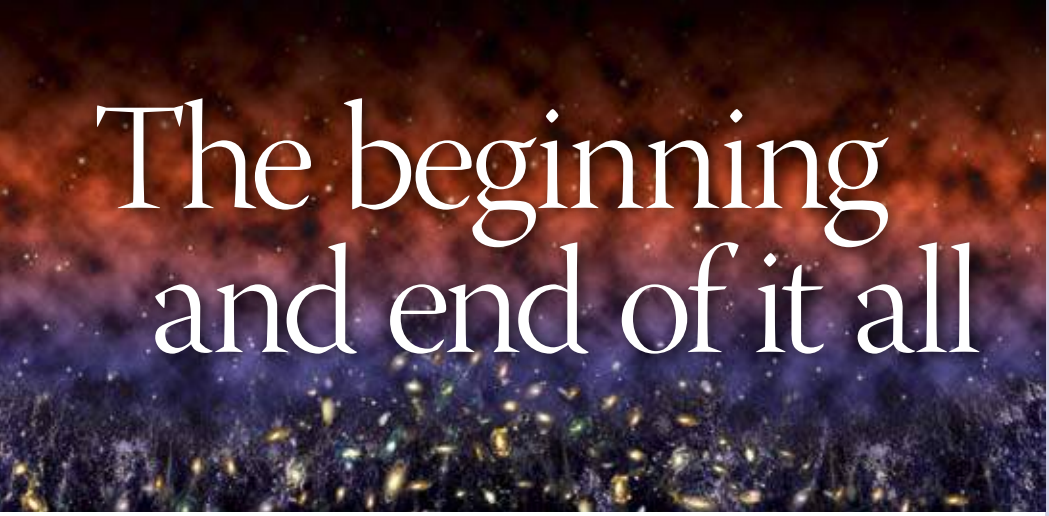
The beginning and end of it all



ASTRONOMY: CHUCK BRAASCH AND ROEN KELLY

Nothing captures people's imaginations like cosmology's big questions.

David J. Eicher

How did the Big Bang happen?

Is cosmic inflation a certainty?

Do cosmic strings control the present-day universe?

How will the observable universe we know end?

These questions, and as much as we know of their answers, tug at the core of what we want to know as human beings: How did we get here? What will happen to our civilization on Earth? Could life permeate the galaxies or is it a rare, ultra-precious — nearly magical — thing?

In *COSMOS*, the editors of *Astronomy* magazine have assembled 15 of the most amazing, illuminating articles about cosmology's biggest topics, covered in the pages of *Astronomy*.

In this special issue, you'll get a comprehensive, clear overview of the origin and fate of the cosmos, relativity, high-energy astrophysics, and the prospects for finding life elsewhere in the universe.

Our writers include scientists working in the field, such as Ray Jayawardhana of the University of Toronto, James Trefil of George Mason University, and Seth Shostak of the SETI Institute. Moreover, some of the nation's best science writers, such as Steve Nadis, Ray Villard, and Bruce Dorminey, have contributed to this special issue.

Avenues of interest to astronomers often lead to research breakthroughs. Among the hottest topics are mysterious neutrinos. Astronomers now know neutrinos have slight mass but don't yet know if these tiny particles contribute to the dark matter that pervades the universe. The reason these enigmatic particles don't exist in greater numbers is not yet understood. In "The great neutrino hunt" (page 44), two British science writers, Alison Boyle and Ken Grimes, examine neutrinos' roles in helping scientists resolve the mysteries of the solar system and beyond.

Other active areas of research splash across these pages: how nearby stars may hold the key to understanding the universe's early days, in Steve Nadis' "Before there was light" (page 12); the secrets held in the dark grasp of low-surface-brightness galaxies, by Bruce Dorminey, in "Darker than the night" (page 74); the story of a planet that formed very early in the universe in a place where it shouldn't have, by Ray Villard, in "The first planet" (page 50); and the story of how astronomers would recognize the characteristics of life elsewhere in the galaxy, by Alan Longstaff, in "Quest for a living universe" (page 92).

Taken together, these 93 pages of science reporting offer a unique and valuable view into the state of astronomical knowledge. Keep it by the fireplace, and enjoy traveling to other worlds from the comfort of your living room!

Yours truly,

David J. Eicher
Editor

COSMOS

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COSMOS 2006 (ISBN 0–89024–693–9) is published by Kalmbach Publishing Co., 21027 Crossroads Circle, P. O. Box 1612, Waukesha, WI 53187–1612. *Astronomy* editorial phone: (262) 796-8776; advertising: (888) 558-1544; customer service and sales: (800) 533-6644; fax: (262) 796-1615; e-mail: customerservice@kalmbach.com. SINGLE COPY PRICE: U.S. $7.95, Canada $9.50, and Foreign $9.50. Canadian price includes GST. BN 12271 3209 RT. Canadian and foreign orders payable in U.S. funds. Canadian International Publications Mail Products Agreement no. 40010760. Expedited delivery available for additional $2.50 domestic and Canadian, $6 foreign.

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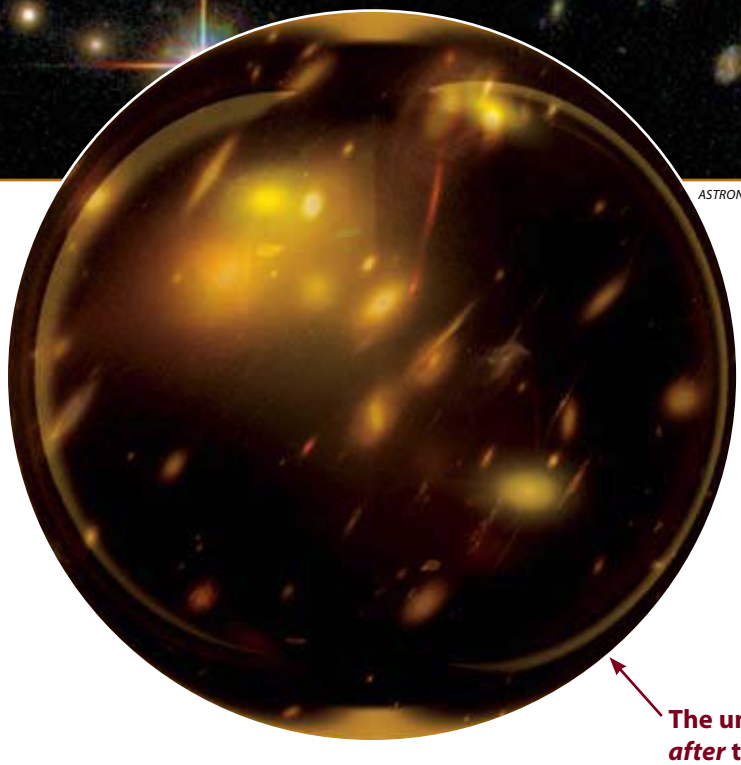
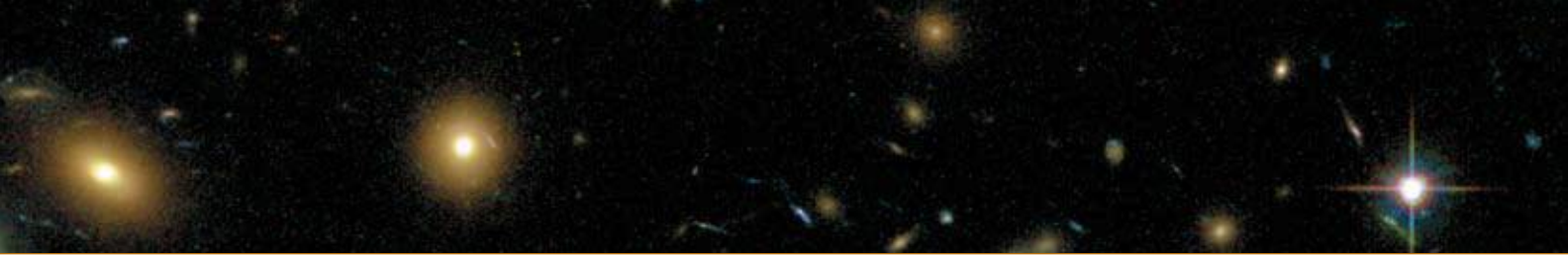


ASTRONOMY: ROEN KELLY AND CHUCK BRAASCH

The universe at actual size *after* the period of hyper-expansion known as inflation

Seeing the dawn of time

Cosmic inflation plugged gaping holes in the Big Bang theory — and turned our universe into one of many. /// BY ADAM FRANK



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Throughout human history, there are times when a single idea has emerged to bring clarity and sow the seed for further progress. Inflationary cosmology is such an idea. Conceived more than 3 decades ago as an answer to vexing questions that haunted astronomers' attempts to make sense of the universe, it has grown a universe of possibilities all its own.

Like all great ideas, inflationary cosmology is radical. It begins by conceiving the universe in a fetal state — a mere instant after creation and at the edge of our understanding of physical laws. Inflation then blows up that universe, driving a brief period of violent expansion that hurtles the cosmos apart at a rate never to be repeated.

From this violent beginning, inflation rescued cosmology from a snake pit of paradoxes. Uniting astronomy and the hairy edge of particle physics, inflation became a new "standard model" for the universe's birth — an essential component of the Big Bang.

In the 30 years since inflation theory was born, it has gone through its own explosion, opening up newer, more extreme ideas for physicists and astronomers to explore. Far from simply breathing new life into the Big Bang model, inflation has given scientists the confidence to speak of a multiverse — a universe of universes — and even ask the question of our own place in this vastly enlarged cosmos.

Beginning with a bang

To understand why inflation theory succeeded where other ideas failed, we first have to understand why it was needed at all. It always makes sense to start at the beginning, but the beginning was the very problem cosmologists faced in the 1970s.

Adam Frank, *a member of* Astronomy's *editorial advisory board, is a physicist at the University of Rochester in New York.*

By the time the decade of disco and punk rock was well underway, the Big Bang had become the standard model for the history of the universe. Big Bang theory rests on the observation that the universe is expanding. Take this idea and run it backward, and you must conclude the universe was smaller, denser, and hotter in the distant past. The further you rewind the cosmological "movie," the smaller, denser, and hotter the universe gets.

The evidence for this early, super-small, super-compressed, and super-hot cosmic epoch is overwhelming. The most critical support for the Big Bang came with the 1964 discovery of the cosmic microwave background (CMB). That year, radio astronomers Arno Penzias and Robert Wilson began working with a new microwave antenna. A low-level hiss plagued the instrument and, despite their best efforts, they were unable to remove it. The bothersome signal remained, regardless of which direction the microwave "telescope" pointed. At first, they did not know what they had stumbled upon, thinking the hiss was just noise from the electronics.

INFLATION HAS GIVEN scientists the confidence to speak of a multiverse — a universe of universes.

After tireless work, they concluded the signal was not noise, but a relic of the distant past. The microwaves came from a time when the universe was a hot, dense plasma — a roiling mix of subatomic particles and light. As the universe expanded and cooled, matter and radiation unmixed, or "decoupled," about 380,000 years after the Big Bang. At that instant, the photons were free to travel unimpeded through space for the rest of cosmic history. Filling every sector of the sky, in every direction, the CMB is a direct link to the Big Bang. Its discovery became a turning point for astronomy — and launched the age of modern cosmology.

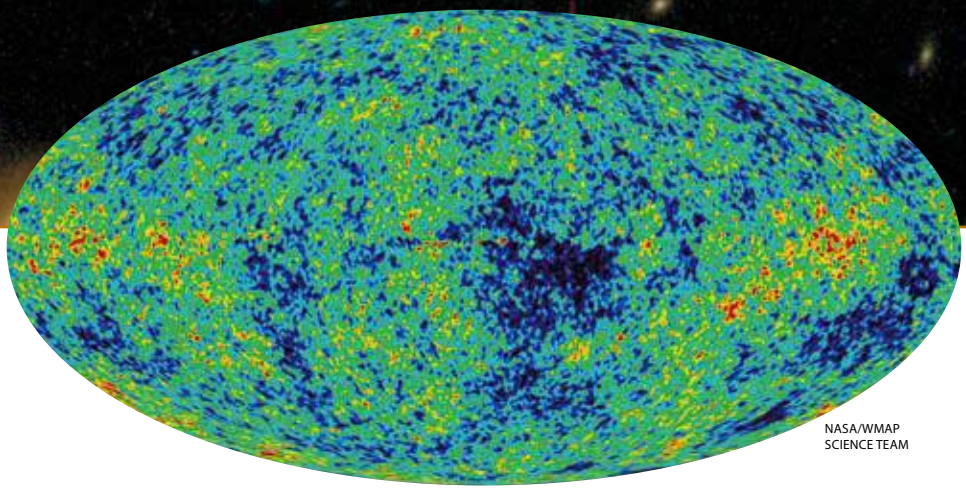
The Big Bang model circa 1975 was a triumph. Researchers actually could say something testable about the young cosmos. But, as observations became more refined and scientists explored the theory in greater detail, troubling dilemmas arose that threatened to topple Big Bang cosmology.

The three whys of inflation

The difficulties facing the Big Bang model came from several directions. Some emerged purely from observations as astronomers acquired better data. Others emerged from the growing interplay between cosmology and particle physics. By the end of the 1970s, three urgent problems loomed.

CAUSALITY PROBLEM: Using the CMB, astronomers could measure the properties of the early universe in different regions of the sky. In particular, they could extract the temperature of the cosmic plasma with great precision.

To their astonishment, they found the temperature remained the same no matter which direction they looked. Even when their instruments pointed in opposite directions, they found the plasma temperature to be the same to one part in 10,000. Why would it be the same everywhere? The universe began as a chaotic, expanding fireball of gas, so it seems reasonable that some parts of the fireball would have ended up with slightly different conditions.



NASA/WMAP SCIENCE TEAM

THE COSMIC MICROWAVE BACKGROUND is a relic of hot radiation emitted when atoms first formed and light could travel freely, 380,000 years after the Big Bang. The smoothness of this radiation suggests the universe expanded at breakneck speed in the first fraction of a second. Colors indicate temperature differences of a few millionths of a degree.

The universe's uniformity on a large scale posed a fundamental problem for astronomers that can be stated simply — cause and effect. "Points on opposite sides of the sky were too far apart when the CMB photons were created," says Sean Carroll, an astrophysicist at the University of Chicago. According to Carroll, regions we now see a hemisphere apart were so distant when the CMB photons decoupled, they could not have had any contact with each other. A light signal could not bridge their separation in the time between the Big Bang and the moment of decoupling. This is the root of the cause-and-effect dilemma.

This means the constant temperatures throughout the universe were an amazing cosmic coincidence. Such coincidences keep astronomers up at night. "If even light didn't have time to make it from one region to the other," says Carroll, "then the different regions couldn't have known about each other. The different regions are too well synchronized [in temperature] to explain with standard Big Bang models." This was the monster problem astronomers and physicists faced in the 1970s. If they could not solve it, their hopes for a rational cosmology might have collapsed.

FLATNESS PROBLEM: In cosmology, a single number describes the universe's "shape" and fate. Finding its value is one of cosmology's Holy Grails. Called Omega, it's a measure of the universe's density expressed in terms of a "critical" value. If Omega equals 1, the universe is flat. This means parallel lines will never converge.

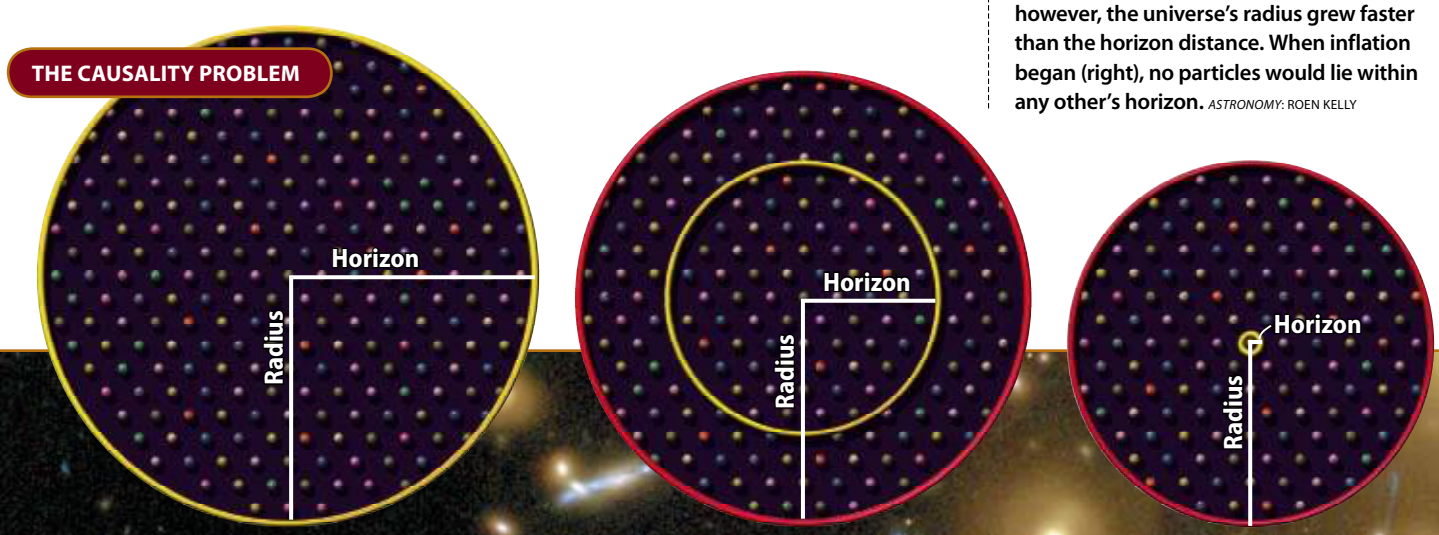
If Omega is greater or less than 1, space is curved and, like seams on a beach ball or a saddle, parallel lines may converge or diverge at cosmic distances. Why is this so important? Einstein, in his general theory of relativity, showed us that the shape of space links to the universe's energy content. The amount of energy also tells us about our eventual cosmic fate — whether the universe will expand forever or one day stop and then start to collapse.

Given its importance, cosmologists have struggled to pin down the value of Omega for decades. In all their attempts, the answer comes out close to — but not exactly — 1. That's a real problem.

If Omega equals 1, then it stays so for all cosmic time. If, however, Omega started off greater or less than 1, then the universe's expansion radically changes Omega's value over time, taking it to extremely small or extremely large values. The fact that we now see Omega being close to 1 means something fishy was going on. Either the value was exactly 1 to begin with and we were missing something, or it was tuned to some special value at the Big Bang that just happened to yield Omega almost 1 at this particular moment in cosmic history.

The last alternative asks for a "fine-tuning" of the initial cosmic conditions, and astronomers would not be happy with yet another coincidence. Astrophysicists wanted a theory that naturally leads to Omega equaling 1.

MAGNETIC MONOPOLE PROBLEM: Electric charges fill the universe. Some are negative, like electrons, and some are positive, like protons. Physicists call these separate polarities electric monopoles.



A PARTICLE CAN INTERACT with others only inside its horizon. Today (left), that's everything in the cosmos. At earlier times, however, the universe's radius grew faster than the horizon distance. When inflation began (right), no particles would lie within any other's horizon. *ASTRONOMY*: ROEN KELLY

One of the strange things about our universe is that no magnetic monopoles have been seen. Every magnetic field comes with both north and south poles, and there are no particles that carry only the north or south "charge." For particle physicists — those who study the fundamental structure of matter — the lack of monopoles seemed weird. In fact, their best efforts to create an all-encompassing model for the nature of matter demanded that magnetic monopoles must have been created during the Big Bang.

Where had all the magnetic monopoles gone? This was the last problem any theory of cosmology had to solve.

"THE DIFFERENT REGIONS are too well synchronized [in temperature] to explain with standard Big Bang models."
— *Sean Carroll*

A marriage of two sciences

Inflation theory began as a bold attempt to solve the problems that plagued cosmologists at the end of the 1970s. The basic idea of inflationary cosmology was simultaneously radical and elegant.

With inflation, cosmologists imagined that the part of the universe we can see underwent a brief period of rapid expansion in its early history. "Early" here may be an understatement. Inflation began when the universe was a mere 10^{-34} second old. That is less than a million billion billion billionth of a second after the Big Bang.

During inflation, the universe expanded by a factor of 10^{43} (that's a 1 followed by 43 zeros), increasing from a fraction of the size of a subatomic particle to the size of a softball. This expansion-on-steroids took place in just 10^{-33} second. After inflation shut down, the universe resumed the more leisurely expansion we see today. For comparison, in the last half of the universe's life (the past 7 billion years), the scale of the cosmos has increased by a factor of only 10.

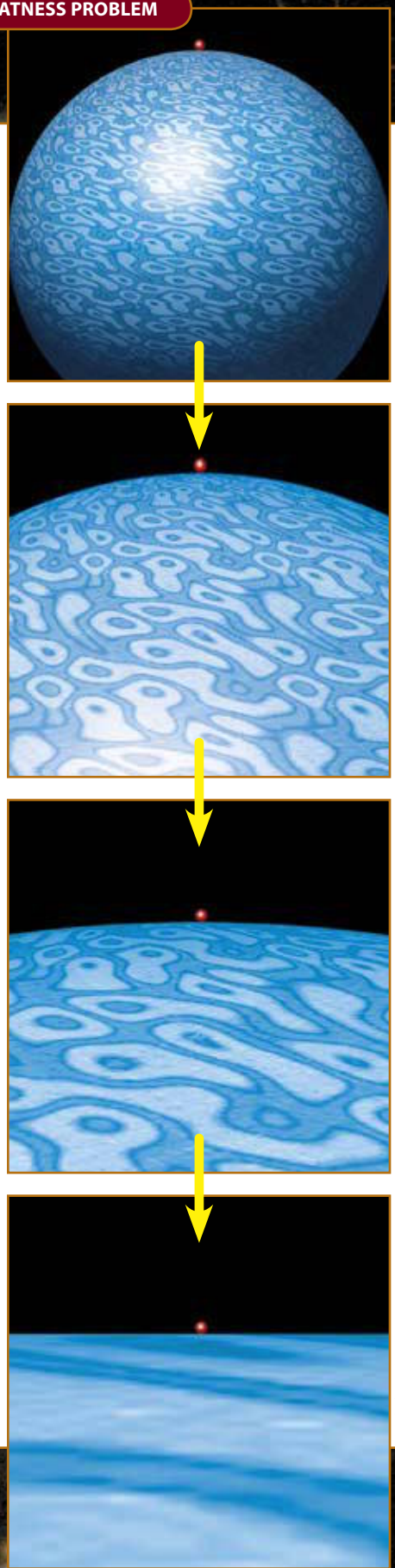
While it may seem like a crazy addition to the Big Bang, inflation's brief period of hyper-expansion solved all the problems with standard cosmology. With inflation, the causality problem disappears because every part of the universe we see today *was* in causal contact before everything was stretched to the extreme.

Inflation's expansion solves the flatness problem by pulling space out so flat that Omega is forced to a value of 1 no matter what its original value. Physicists were happy to have a theory that didn't require any fine-tuning of the universe's initial conditions.

Finally, inflation does away with the magnetic monopole problem by sweeping monopoles so far away in the period of rapid expansion that the odds of us observing one become essentially zero. With this single change to the Big Bang model, the three big problems were resolved. It was hard for physicists and astronomers not to take notice.

Every good idea needs a champion, and inflation found one in Alan Guth, a physicist at the Massachusetts Institute of Technology. In 1981, Guth wrote a paper describing an inflationary model for cosmology. While some of the ideas had been proposed before, Guth brought them together in a coherent, accessible way and added the catchy name "inflation."

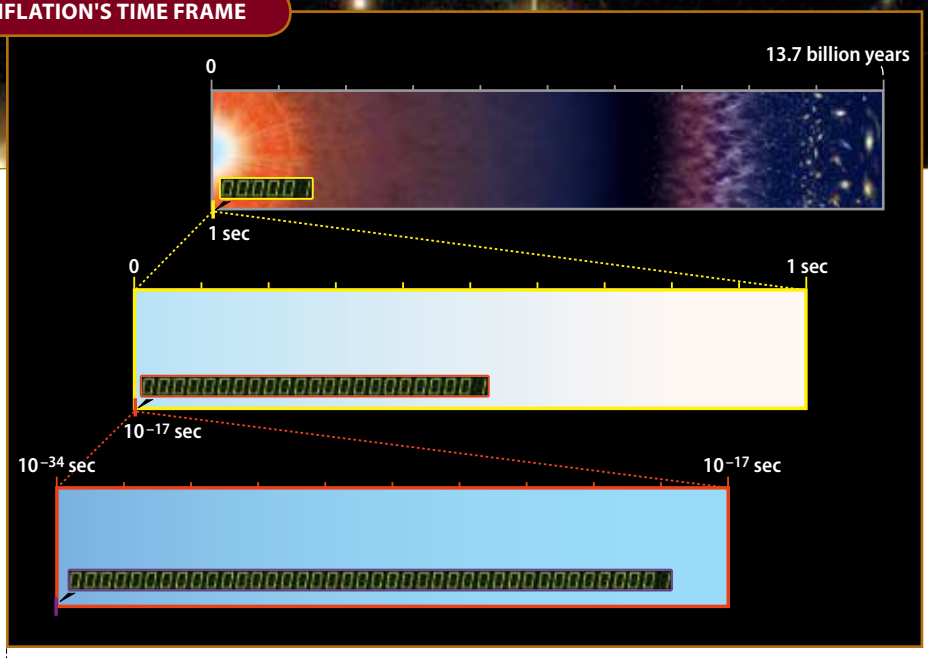
THE FLATNESS PROBLEM



INFLATION MADE THE UNIVERSE FLAT. A curved surface (top) expands by a factor of 3 in each subsequent panel. The sphere in the bottom view appears nearly flat. To relive cosmic inflation, repeat this expansion 87 more times.

ASTRONOMY: ROEN KELLY

INFLATION'S TIME FRAME



HOW MUCH IS 10^{-34} SECOND? Compare 1 second to the 13.7-billion-year age of the universe. Next, divide that second into an equivalent number of parts to get 10^{-17} second. Do that again, and you'll get back to inflation's beginning. *ASTRONOMY:* ROEN KELLY

What mattered most, however, was that Guth was not an astronomer. He was a particle physicist and built his inflation theory using tools from grand unification theories (GUTs).

GUTs have been at the forefront of physics for decades. They represent the grand attempt by theoretical physicists to understand the structure of matter and its interactions at the deepest level. There are four known forces in our universe: gravity, electromagnetism, the strong nuclear force, and the weak nuclear force. These are the only ways particles can affect one another.

Particle physicists suspected these forces were different facets of a single "superforce." They predicted that if the cosmos could be heated to ever higher energies, each force would sequentially "melt" into the superforce just like ice crystals melt into liquid water.

Of course, the entire universe already had been through a stage when it was as hot as any physicist could ever want. Cosmology gave physicists their laboratory. Guth and those who followed built their inflationary cosmology with ideas taken from GUTs. The critical link between the two was the energy source that drove inflation.

Drawing on GUTs, Guth and others imagined the early universe to be pervaded by a field of energy, a background that mimicked empty space but had energy to burn. They called it the "false vacuum." Extending uniformly throughout space, the false vacuum energy field was unstable like a pencil standing on its point. Sooner or later, the false vacuum had to "decay" into a real vacuum, and the energy in the field would be released.

Inflation was the result of that decay. Kicking in just as the universe cooled to the right temperature, the energy released acted as a kind of anti-gravity force. It repelled space-time itself, providing just the right amount of push for just the right amount of time to inflate a cosmic mote into the entire observable universe.

By building inflation from the framework of particle physics and GUTs, Guth and his successors united the realms of the very small with the very large. Inflation has drawn its relevance by bringing cosmology and physics into a coherent whole. This effort continues to bear fruit.

Meet the multiverse

In the years since Guth wrote his first paper, there have been many modifications and variations on the idea of inflation. As Mario Livio of the Space Telescope Science Institute in Baltimore puts it: "Inflation is more of a class of theories than an individual theory."

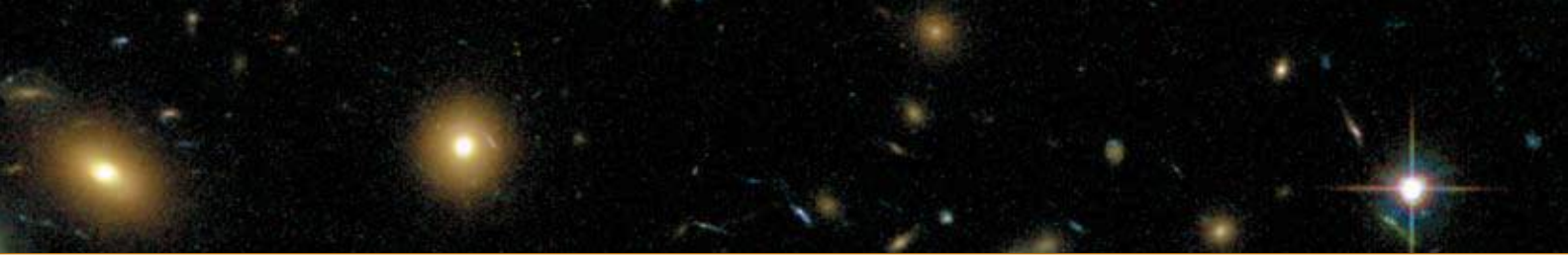
Much of the newer work has focused on the inflation field itself. In the last 30 years, physicists have explored the various mechanisms that can drive rapid cosmic expansion. Another line of inquiry has looked deeper at the assumptions inherent to inflation. From this work has come a more unorthodox understanding of the very concept of cosmology's subject matter.

The basic idea of inflation is that a small portion of the cosmos gets hyper-expanded into the entire observable universe. Even a moment's reflection will tell you there's more cosmos than we can see. What about the rest of it? As physicists and astronomers considered this question, they realized inflation may demand that there be a lot more out there.

"All inflation theories share the same characteristics," says Livio. "They all create a repulsive-gravity phase of the early universe and they grab a speck of space and blow it up by a factor of about 10^{50}. What they have also done is open up the possibility of eternal inflation." According to Livio, eternal inflation is an idea that raises the stakes on what we think of as the universe.

MULTIPLE UNIVERSES

EARTH EXISTS only because the physical laws in our universe are just right. That's a natural result of the multiverse, from which countless pocket universes bubble off from the whole. *ASTRONOMY:* ROEN KELLY AND CHUCK BRAASCH



Imagine a piece of the universe that is undergoing inflation. Then imagine that only a small portion makes the complete transition from the false vacuum state to the real vacuum state. This "pocket universe," as Livio calls it, will continue to expand at a normal rate and perhaps go on to evolve galaxies and stars and planets and living, thinking creatures.

Meanwhile, all around it is a vast region of space and time still undergoing inflation. Why wouldn't other pieces of this inflating cosmos undergo their own transitions to a real vacuum state? "You can end up with a huge ensemble of pocket universes," says Livio.

"ALL INFLATION theories … grab a speck of space and blow it up by a factor of about 10^{50}." — *Mario Livio*

This mix of pocket universes surrounded by a still-inflating false vacuum is what physicists now call the multiverse, and it requires a dramatic reassessment of the very meaning of the word cosmos. It may also be inescapable.

"Inflation naturally produces a multiverse," says Livio. "If you believe in some form of inflation, then it is almost inevitable that some form of eternal inflation will occur."

Our mediocre universe

If all those extra pocket universes exist, it would seem physicists have a lot more to study. The multiverse, however, is not so transparent. "The different universes would not be causally connected," explains Livio. No signals from one pocket universe could ever reach another, which means there is no way to study them. In spite of this cosmic barrier, there may be ways to tell something about the multiverse just by looking at our little pocket of reality.

Physicists have long known the nature of physical laws in our universe may be an accident. Just as ice crystals form in a seemingly random pattern, the exact way our forces froze out of the superforce could have been different if cosmic history were run again. Gravity might have been stronger or weaker, for example.

Changing something like the force of gravity or electromagnetism even slightly alters all cosmic history with respect to the creation of life. Weaker gravity means stars never form, and that means no life. Stronger electromagnetism means biomolecules can't form, and that means no life.

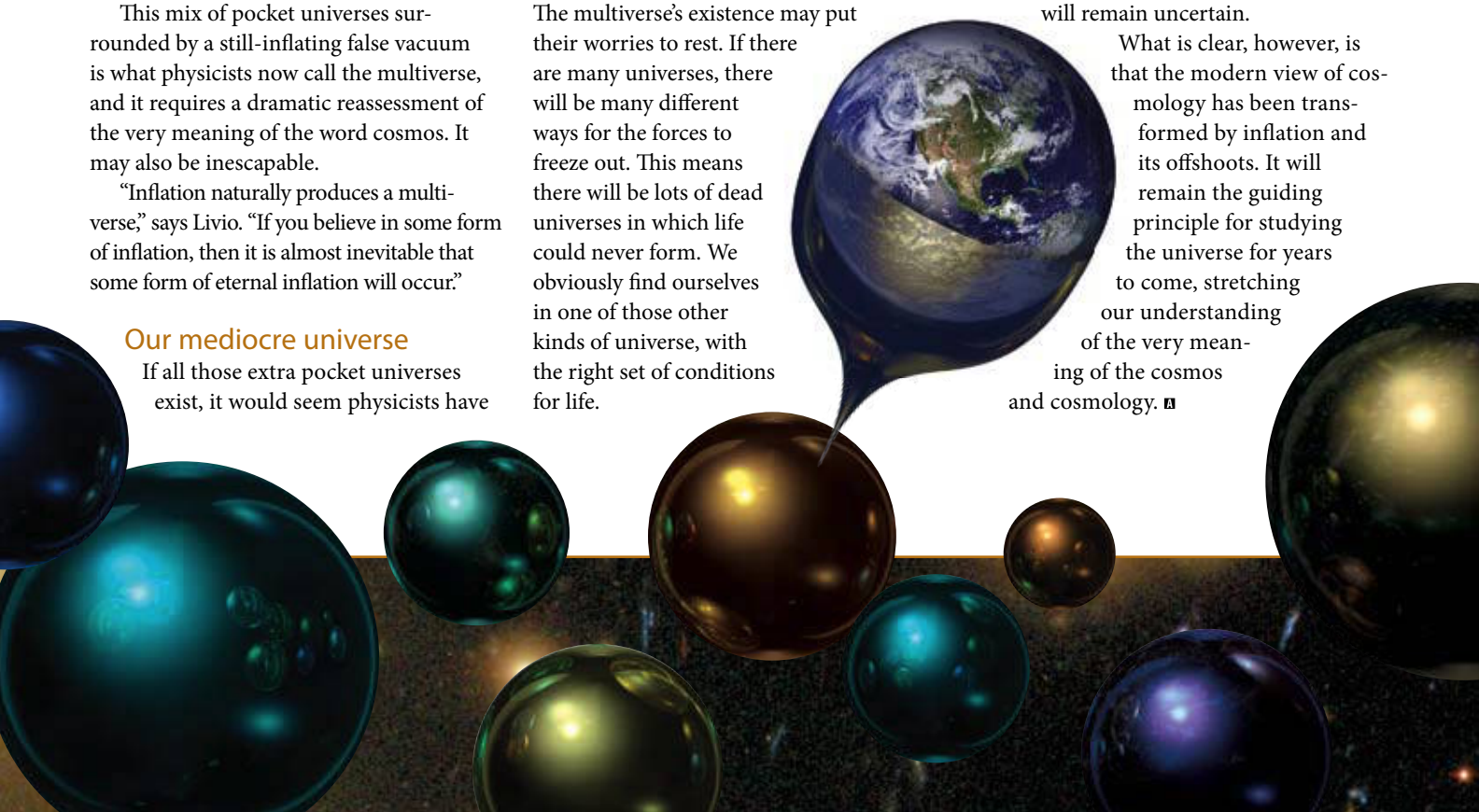
As you might expect, this apparent fine-tuning of physical laws to allow life has bothered some physicists for many years. The multiverse's existence may put their worries to rest. If there are many universes, there will be many different ways for the forces to freeze out. This means there will be lots of dead universes in which life could never form. We obviously find ourselves in one of those other kinds of universe, with the right set of conditions for life.

Some researchers have taken this reasoning even further, arguing that because we wouldn't expect to end up in a "special" universe (that would be more fine-tuning), our conditions must be similar to those that any randomly chosen universe would end up with. So, one can use our existence to say something about the statistics of pocket universes in the multiverse. As you might imagine, this idea — like the existence of the multiverse itself — is a hotly debated point.

From the false vacuum to the multiverse, inflation has transformed the way scientists view cosmic history and the stuff of cosmology. What began as a radical solution to a suite of paradoxes has grown into an ever-expanding paradigm for viewing what is and what can be.

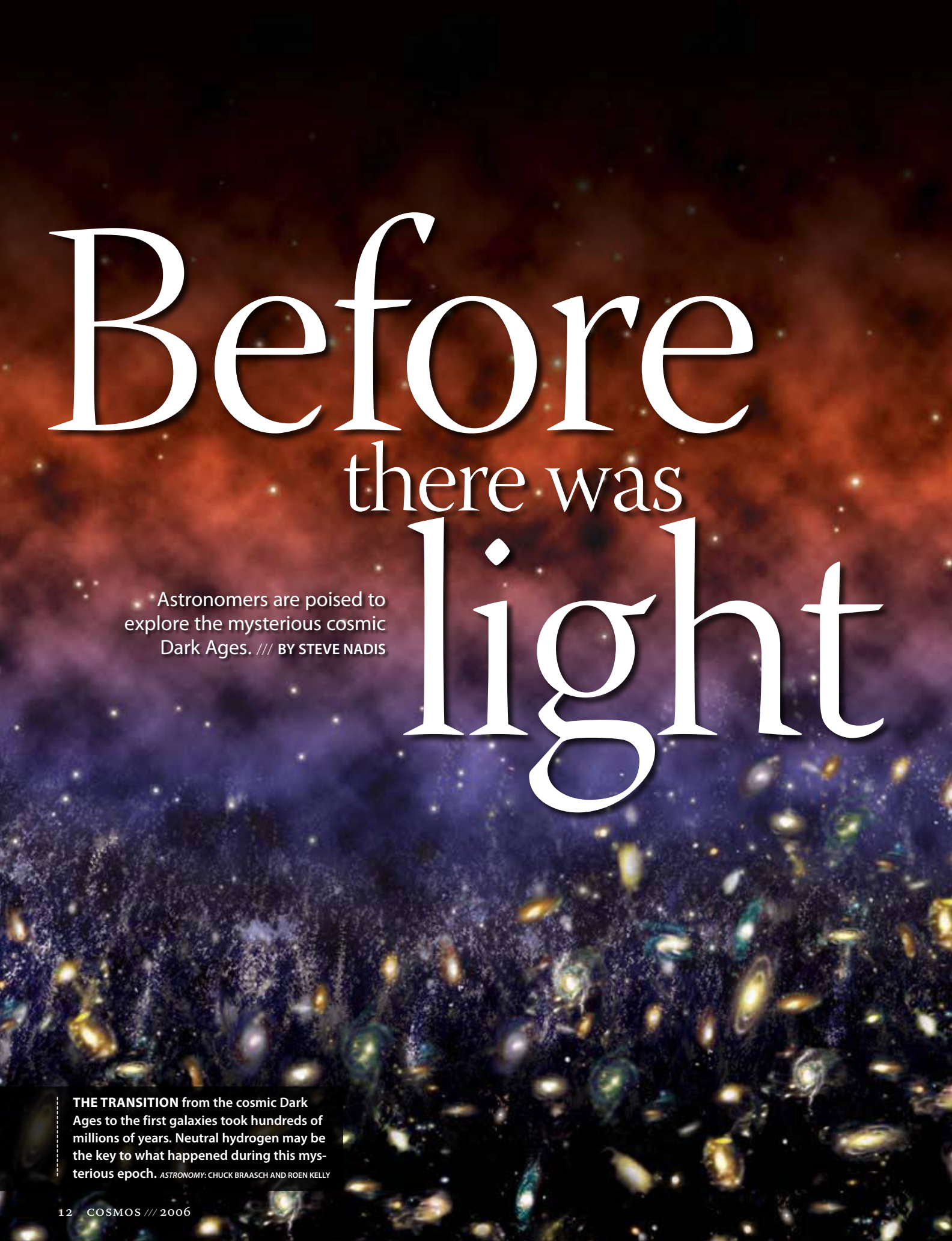
For all its successes, however, inflationary cosmology remains a theory. Because it deals with such small distances, early cosmic times, and high energies, it lies beyond the reach of laboratory study. Although it is consistent with all current cosmological observations, there has yet to be a direct test of its predictions. Thus, its fate and the fate of all the universes it seems to predict will remain uncertain.

What is clear, however, is that the modern view of cosmology has been transformed by inflation and its offshoots. It will remain the guiding principle for studying the universe for years to come, stretching our understanding of the very meaning of the cosmos and cosmology.



Before there was light

Astronomers are poised to explore the mysterious cosmic Dark Ages. /// **BY STEVE NADIS**



THE TRANSITION from the cosmic Dark Ages to the first galaxies took hundreds of millions of years. Neutral hydrogen may be the key to what happened during this mysterious epoch. *ASTRONOMY:* CHUCK BRAASCH AND ROEN KELLY

Cold dark matter models of Big Bang cosmology predict the emergence of structure during the "Dark Ages" — the period after the Big Bang's heat was unleashed and before the first luminous sources turned on — but direct evidence is hard to come by.

Dark matter is invisible, by definition, and has eluded detection efforts. However, the most abundant element of "ordinary matter," hydrogen, has a convenient observational signature. To astronomers hoping to probe this cosmic dark era, neutral hydrogen's 21-centimeter line may be all they have.

A neutral hydrogen atom consists of one proton and one electron. The electron's direction of "spin" — spin is an intrinsic property of particles — can be either aligned with or opposed to that of the proton. The atom has slightly greater energy if the spins are aligned. Because of this, when the electron flips its spin from aligned to opposed — from a higher to a lower energy state — it emits energy in the form of a photon with a wavelength of 21 centimeters [see "At the atomic level," page 14].

"That's why everyone is so excited about hydrogen's 21-centimeter line," says Ger de Bruyn of ASTRON, the Netherlands Foundation for Research in Astronomy.

So where's the signal?

Radio telescopes will be used to track primordial hydrogen because any 21cm radiation from early epochs has been stretched to meters-long radio waves by the universe's expansion. Because of this, the new telescopes will look at wavelengths between 1.5 and 5.3 meters. Snaring these long-wavelength signals, says Harvard theorist Lars Hernquist, "is the next big frontier in observational cosmology" — a sentiment shared by the people behind the telescopes.

Indeed, radio-astronomy activity abounds these days, as researchers prepare to hunt for the "cosmic hydrogen background." Prototypes have already been built for several radio surveys: the LOw-Frequency ARray (LOFAR) in the Netherlands; the PrimevAl Structure Telescope (PAST) in China; and the Mileura Widefield Array (MWA) in Australia. "This is not just a few experiments," notes Massachusetts Institute of Technology (MIT) astrophysicist Miguel Morales. "It's the birth of a field."

Jeff Peterson, a Carnegie Mellon physicist coleading PAST with Xiang-Ping Wu of China's National Astronomical Observatory, is looking forward to practicing astronomy at redshift 17, some 200 million years after the Big Bang. "We have quasar astronomy at redshift 6 — a billion years after the Big Bang — and cosmic microwave background [CMB] astronomy at redshift 1,000 — a few hundred thousand years after the Big Bang — but nothing in between," he says. "Here's a chance to see 5 times farther than Hubble or Sloan [Digital Sky Survey] — a chance to advance astronomy fivefold."

> "This is not just a few experiments. It's the birth of a field." — *Miguel Morales*

Astronomers hope to figure out where neutral hydrogen has accumulated over time and when it reverted to its ionized form. Space now contains vast regions of ionized hydrogen, designated HII. After the Big Bang, all gas was hot and ionized. The universe cooled as it expanded, and hydrogen became neutral, with its constituent protons and electrons joining together as neutral hydrogen at the moment of recombination. The CMB followed shortly afterward.

Neutral gas in the intergalactic medium reionized hundreds of millions of years later — the exact time is still to be determined — when it was heated by radiation from early stars, galaxies, and quasars. The universe went from ionized to neutral and back to ionized.

The last phase, called reionization, may be discernible as a bump in the sky's radio background. "Our best chance of detecting the reionization signal is if the neutral gas disappeared quickly," explains Steve Furlanetto of the California Institute of Technology. If the change was gradual, it will be harder to pick out amid the background noise of the Milky Way and other galaxies.

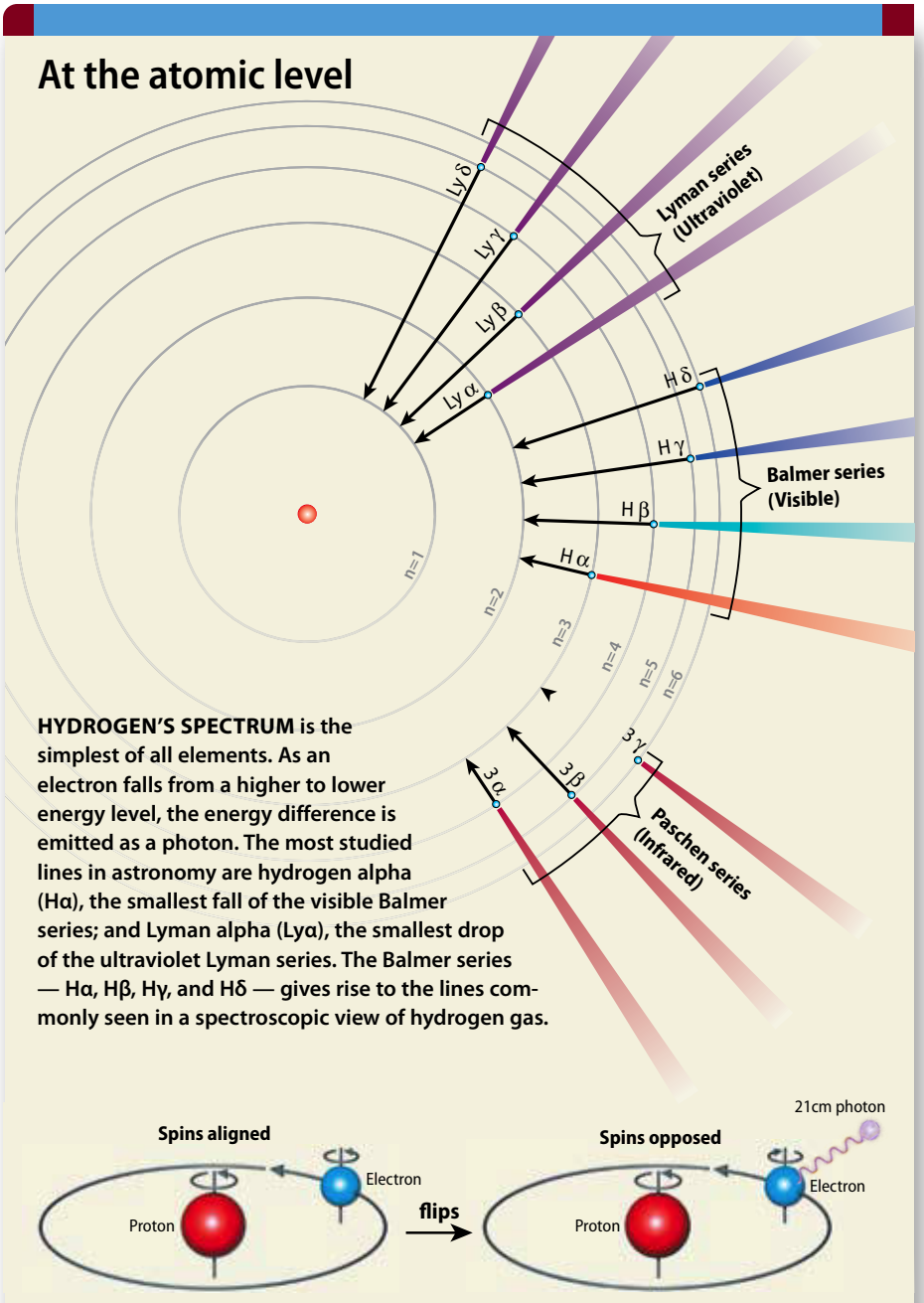
If astronomers can determine the frequency of the "bump" in the radio spectrum when the neutral gas abruptly vanished, they'll immediately know the redshift, which will tell them when reionization happened. Next, they'll look for how it happened: In other words, what sources lit up the universe?

Zooming in on reionization

The origin of the first stars has fascinated humans for centuries, but interest in the reionization epoch is more recent. The research gained momentum in 2003, when investigators on the Wilkinson Microwave Anisotropy Probe (WMAP) team announced that reionization of the universe's intergalactic gas likely occurred roughly 200 million years after the Big Bang, rather than 1 billion years after, as previously thought.

WMAP narrowed down the onset of reionization to between 100 million years (redshift 30) and 400 million years (redshift 11) after the Big Bang, but it could not follow the process over an extended period of time. If reionization occurred early, at redshift 30, it's doubtful any neutral-hydrogen instruments under development will have the sensitivity to detect it. Background emissions from radio galaxies are noisier at low frequencies because galaxies — including the Milky Way — give off more low-energy, and hence low-frequency, photons than high-energy photons.

An analysis of two distant quasars' absorption spectra observed by the Sloan Survey suggests more than 10 percent of the universe's hydrogen was still neutral 900 million years after the Big Bang, according to Harvard's Abraham Loeb and University of Melbourne's Stuart Wyithe. The findings were welcome news to MIT radio astronomer Jacqueline Hewitt, who heads MWA's reionization group. "That means it's worth doing this experiment because reionization is still going on," Hewitt says. Even with


At the atomic level
Lyman series (Ultraviolet)
Balmer series (Visible)
Paschen series (Infrared)
Lyδ
Lyγ
Lyβ
Lyα
Hδ
Hγ
Hβ
Hα
3γ
3β
3α
n=1
n=2
n=3
n=4
n=5
n=6
HYDROGEN'S SPECTRUM is the simplest of all elements. As an electron falls from a higher to lower energy level, the energy difference is emitted as a photon. The most studied lines in astronomy are hydrogen alpha (Hα), the smallest fall of the visible Balmer series; and Lyman alpha (Lyα), the smallest drop of the ultraviolet Lyman series. The Balmer series — Hα, Hβ, Hγ, and Hδ — gives rise to the lines commonly seen in a spectroscopic view of hydrogen gas.
Spins aligned
Electron
Proton
flips
21cm photon
Spins opposed
Electron
Proton

ZOOMING IN ON THE LOWEST ENERGY LEVEL — neutral hydrogen's ground state, n=1 in the top diagram — the electron's spin can be either aligned to the proton's spin (left) or opposed (right). As the electron's spin flips from the higher energy state to the lower energy state, it will emit a 21cm wavelength photon. *ASTRONOMY*: ROEN KELLY

present capabilities, she adds, "There should be something to see."

Experimental variety

Some technology used in these efforts is not new. "A telescope like PAST could have been built years ago, but no one made the investment," says Peterson. He and his fellow astronomers are deploying standard TV and radio antennae — items that can be purchased at a local electronics store.

The ingenuity lies in linking large numbers of these devices in sophisticated ways to make them perform like one large dish. "It takes a lot of computing power to bring the information together, but computing costs keep falling, unlike the cost of steel," notes Morales. "It's an inexpensive way of increasing your sensitivity."

The main projects now underway — LOFAR, PAST, and MWA — all rely on multiple antennae with no moving parts, but their search strategies differ. PAST will point in just one direction — the North Celestial Pole — gaining deep observations of a small field of view.

Of these projects, LOFAR has the longest baseline, a 62-mile-diameter (100 kilometers) array, which offers the greatest sensitivity. MWA is just a mile (1.5 km) across but has the largest field of view. By surveying the sky for longer times, MWA astronomers hope to match LOFAR's sensitivity. Before long, says Morales, "We'll see who guessed right."

Having different instruments with different designs is critical, says Peterson, "because this is difficult astronomy, possibly more difficult than the CMB." While most challenges for CMB astronomy are technical in nature, the main problems for 21cm astronomy lie in the sky.

The radio background's temperature is 200 Kelvin — 75 percent of which is from the Milky Way, 25 percent from other radio galaxies and quasars. Whereas the neutral-hydrogen signal is a mere 20 millikelvin — 10,000 times dimmer. "We can't identify individual radio galaxies and remove their signals," Peterson says.

Meanwhile, the ionosphere — a layer of ionized particles between 50 and 200 miles (80–320 km) above Earth's surface — intermittently reflects radio waves, creating havoc for radio astronomers. At higher redshifts, the problem gets worse.

Radio-frequency interference from television and radio transmitters and airplanes further confounds matters. "It's definitely going to be hard," admits Chris Carilli of the National Radio Astronomy Observatory. "If it were easy, we'd have done it already."

Resolving a history

Astronomers have been spurred on by the potential payoff. "21cm measurements offer the richest data set on the universe's initial conditions that we can see on the sky," says Loeb. Calculations he did with Harvard colleague Matias Zaldarriaga show neutral-hydrogen anisotropies "contain an amount of information orders of magnitude larger than any other cosmological probe," says Loeb.

Whereas CMB measurements are taken at a single redshift — one moment in time

Steve Nadis, *an* Astronomy *contributing editor, lives in Cambridge, Massachusetts.*

— neutral-hydrogen measurements can look at numerous redshifts, and hence different times. The result should be the universe's definitive history of hydrogen.

To search the Dark Ages, astronomers have designed instruments to explore both available spectra: absorption and emission. In early epochs, when the universe's gas was colder than the microwave background, neutral hydrogen absorbed CMB flux, leaving a telltale imprint on the low-frequency (radio) end of the spectrum.

Astronomers can trace neutral hydrogen's distribution in this era by finding regions with fewer CMB photons. The technique, according to Loeb and Zaldarriaga, could detect hydrogen clumps in the nascent universe 300 light-years across — a resolution roughly 1,000 times better than WMAP's.

Once neutral hydrogen is heated above the CMB temperature by the first stars (but before reionization), the gas will emit 21cm radiation. Says Carilli, "The 21cm line is the only direct probe we have of the neutral intergalactic medium."

The absorption signal has a lower frequency, and therefore, longer wavelengths than the emission signal, which occurred in a different epoch.

Bubbly universe

The distribution of this neutral gas, in turn, can reveal whether the ionizing sources are stars or quasars. Each primordial light source carves out a bubble of ionized gas within an otherwise neutral sea. Over time, the bubbles expand and overlap until reionization is complete.

Two scenarios exist. Either stars and galaxies caused ionization or quasars were to blame. Each leads to a geometrically distinct picture. "If quasars dominated the process, there should be a small number of large bubbles," explains Loeb. "If normal galaxies drove reionization, there'd be a large number of small bubbles."

From an observational standpoint, bubbles around quasars are the easiest places to start probing reionization because they're dramatic features whose positions are well known. Lincoln Greenhill of the Harvard-Smithsonian Center for Astrophysics intends to use the Very Large Array (VLA) in New Mexico to study these bubbles.

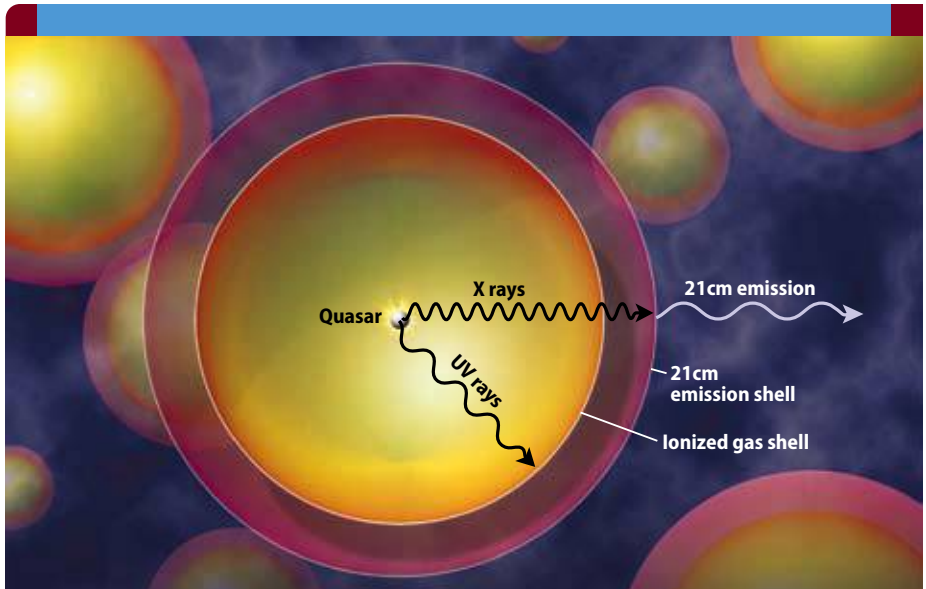
In collaboration with Carilli and others, Greenhill wants to install a dipole antenna on each of VLA's 27 dishes to intercept low-frequency radio signals. The initial plan is to examine the three most distant quasars, all lying beyond redshift 6.2 in the reionization epoch.

When other far-flung quasars are discovered, they'll be added to the list. By taking advantage of VLA's existing infrastructure, says Greenhill, "We can do this fast and cheap." With the Smithsonian Astrophysical Observatory covering the $100,000 equipment costs, they just need to secure telescope time.

Greenhill and his colleagues will focus on the thin "emission shell" lying at the edge of the bubble — the most likely source of 21cm radiation. X rays from the quasar penetrate and heat the neutral gas, giving rise to 21cm emissions.

The quasar's ultraviolet photons, which the neutral medium absorbs strongly, ionize the gas and thereby cease emissions [see "Making bubbles in space," below]. Greenhill hopes to determine the size and growth rate of the bubbles, while gathering details about the surrounding medium.

After first tackling the most extreme cases, radio astronomers will attempt to observe ever-smaller fluctuations until the neutral hydrogen background is fully mapped. The ultimate goal, says Carilli, is "3-D tomography" — the equivalent of a CT scan of the universe. "Instruments like LOFAR won't have the sensitivity for this experiment, but all hope is not lost," he says. "Unlike WMAP, the COsmic Background Explorer, did not map the CMB. Instead, it made a statistical measurement,



MAKING BUBBLES IN SPACE

A 21CM EMISSION SHELL is always radiating away just ahead of the shell of ionized gas. By looking for these shells, or bubbles, astronomers will be able to map reionization.

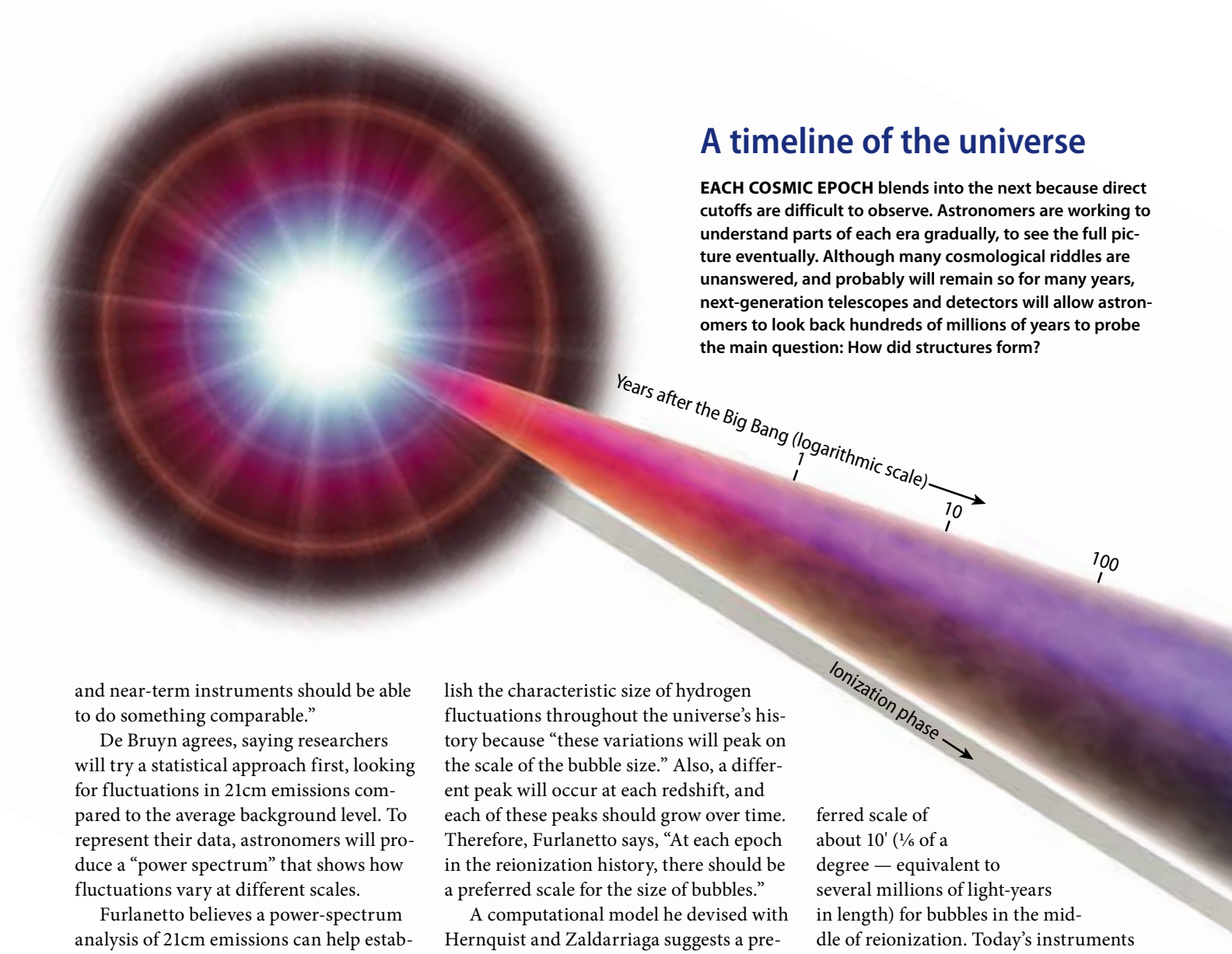
Quasars emit both X-ray and ultraviolet (UV) photons. Although both types of photons travel at the speed of light, higher-energy X rays interact less with the surrounding media, and thus get out faster. UV photons ionize most of the neutral hydrogen because they are more abundant and the gas absorbs these lower-energy photons more easily. Energy from the UV photons ionizes the hydrogen by stripping away electrons from the hydrogen nuclei. As ionization continues — primarily by UV photons — a cavity of ionized gas forms and grows around the quasar, just like a steadily inflating bubble.

The X rays propagate through the gas with less energy loss — and penetrate farther — because they are less likely to be absorbed. They heat the gas, therefore, without ionizing it, giving rise to 21cm radiation. As X rays propagate outward from the quasar, a thin emission shell — where 21cm emission takes place — forms just beyond the ionized bubble. When the UV photons reach this shell, the gas ionizes, and emission ends. At that point, the X rays have penetrated farther into the neutral medium to heat the outlying neutral hydrogen, causing additional 21cm radiation. The emission shell moves outward radially, always one step ahead of the UV-driven ionization front. — *S. N.*

ASTRONOMY: ROEN KELLY

A timeline of the universe

EACH COSMIC EPOCH blends into the next because direct cutoffs are difficult to observe. Astronomers are working to understand parts of each era gradually, to see the full picture eventually. Although many cosmological riddles are unanswered, and probably will remain so for many years, next-generation telescopes and detectors will allow astronomers to look back hundreds of millions of years to probe the main question: How did structures form?



and near-term instruments should be able to do something comparable."

De Bruyn agrees, saying researchers will try a statistical approach first, looking for fluctuations in 21cm emissions compared to the average background level. To represent their data, astronomers will produce a "power spectrum" that shows how fluctuations vary at different scales.

Furlanetto believes a power-spectrum analysis of 21cm emissions can help establish the characteristic size of hydrogen fluctuations throughout the universe's history because "these variations will peak on the scale of the bubble size." Also, a different peak will occur at each redshift, and each of these peaks should grow over time. Therefore, Furlanetto says, "At each epoch in the reionization history, there should be a preferred scale for the size of bubbles."

A computational model he devised with Hernquist and Zaldarriaga suggests a preferred scale of about 10' (⅙ of a degree — equivalent to several millions of light-years in length) for bubbles in the middle of reionization. Today's instruments are aiming for that same scale.

Good "seeing"

Initially, LOFAR will look for the characteristic sizes of ionized hydrogen bubbles; its search begins around 2007. The array will comprise 15,000 antennae deployed in a five-arm spiral spread out over a 62-mile-diameter (100 km) area in its initial phase. Morales is skeptical about LOFAR's chance for success in such a densely populated area. With competing radio and TV signals, he says "It's like doing astronomy in an outdoor disco."

De Bruyn is confident his team can deal with those challenges, but he acknowledges the site's shortcomings. For starters, they'll have to curtail observations at redshift 11.5 to avoid interference from FM radio broadcasts. But optical astronomers also have to adapt to clouds and inclement weather, he says. "Not everyone can observe in Hawaii or Chile.

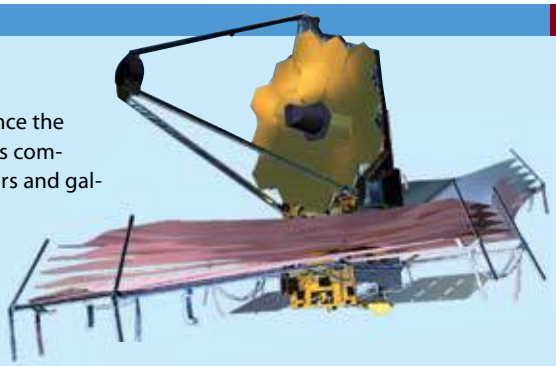
THE ERA OF LIGHT

The cosmic Dark Ages ended once the universe's neutral hydrogen was completely reionized by the first stars and galaxies. The luminous period that followed holds almost as many questions as the Dark Ages.

Because astronomers know important steps in structure formation occurred shortly after the Dark Ages ended and the stars ignited, they want to explore this era soon. One of the instruments astronomers are pinning their hopes on is the James Webb Space Telescope. NASA plans to launch that instrument in 2013.

With the formation of the first galaxies, dust absorbed starlight and re-emitted infrared radiation. Astronomers think light from this process created a "cosmic infrared background." By studying this light, astronomers can observe the "structural clumpiness" of the early universe.

The infrared radiation traces early protogalaxies, helping us understand how the universe's structure evolved. — *Liz Kruesi*



SCHEDULED FOR A 2013 LAUNCH, the James Webb Space Telescope — Hubble's infrared successor — will look back to early galaxy formation.

NORTHROP GRUMMAN SPACE TECHNOLOGY

Just because one site is best doesn't mean other sites can't support good science."

In contrast to LOFAR's crowded setting in the Netherlands, PAST sits in the remote Ulastai Valley of western China, shielded from interference by high mountains. "We can choose our frequencies on the basis of cosmology," says Peterson, rather than the whims of FM broadcasting. With a goal of 10,000 antennae installed upon completion of the project, PAST will survey the regions that existed 200 million years after the Big Bang, before they grew into the large-scale structures we see today.

In Australia, MWA has a similar target, aiming for great big lumps of neutral hydrogen that will eventually become galaxy clusters, rather than individual galaxies. Although PAST will have a larger collecting area — 80,000 square meters versus MWA's 8,000 — MWA can point in any direction. "We'll look for holes in the galactic radio emissions," says Morales, "seeking out the quietest, darkest places in the sky." Test observations began in March 2005. Current plans call for an early 2007 start date, assuming the U.S. team can contribute its share of the cost.

Groundwork for the future

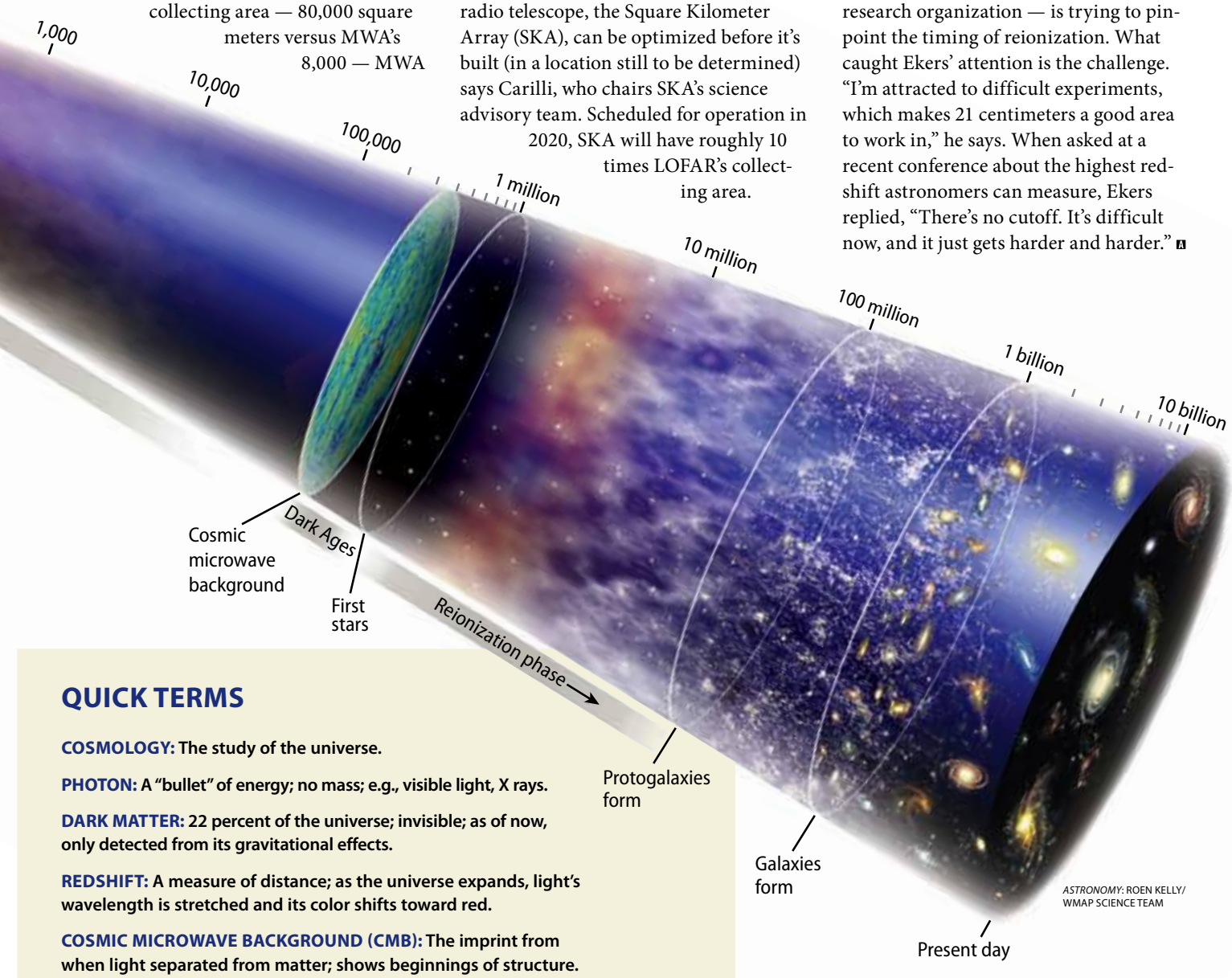
The neutral-hydrogen signal will have to be confirmed by more than one instrument because of its faintness on the radio sky. Verification has proved crucial in CMB findings, notes Peterson, and it underscores the value of having multiple instruments and multiple approaches.

These early "pathfinder experiments" can help astronomers confront challenges posed by the ionosphere, radio galaxies, and interference so the next-generation radio telescope, the Square Kilometer Array (SKA), can be optimized before it's built (in a location still to be determined) says Carilli, who chairs SKA's science advisory team. Scheduled for operation in 2020, SKA will have roughly 10 times LOFAR's collecting area.

With the added sensitivity, says Carilli, "We can go from imaging the most extreme objects in the universe to imaging normal objects." The goal is to examine small angular scales to chart the early clumpiness of neutral hydrogen, which should tell astronomers about structure formation, inflation, dark matter, and other cosmic riddles.

If things go well, and SKA lives up to its billing, there's the potential to extract a wealth of information from the neutral-hydrogen signal, says Zaldarriaga. But he still considers the proposition dicey. "Whether or not this can be done in practice remains to be seen."

Ron Ekers, a radio astronomer based at the Commonwealth Scientific and Industrial Research Organization (CSIRO) — Australia's national scientific research organization — is trying to pinpoint the timing of reionization. What caught Ekers' attention is the challenge. "I'm attracted to difficult experiments, which makes 21 centimeters a good area to work in," he says. When asked at a recent conference about the highest redshift astronomers can measure, Ekers replied, "There's no cutoff. It's difficult now, and it just gets harder and harder." ■



ASTRONOMY: ROEN KELLY/ WMAP SCIENCE TEAM

QUICK TERMS

COSMOLOGY: The study of the universe.

PHOTON: A "bullet" of energy; no mass; e.g., visible light, X rays.

DARK MATTER: 22 percent of the universe; invisible; as of now, only detected from its gravitational effects.

REDSHIFT: A measure of distance; as the universe expands, light's wavelength is stretched and its color shifts toward red.

COSMIC MICROWAVE BACKGROUND (CMB): The imprint from when light separated from matter; shows beginnings of structure.

In search of the first

Detecting the earliest stars will help astronomers unlock secrets of the infant universe. /// BY RAY JAYAWARDHANA

Looking up at the star-studded sky on a clear night, it's difficult to imagine there was a time when the universe contained no stars, no galaxies, no shining celestial bodies of any kind. Yet, for a significant stretch of the first roughly 100 million years after the Big Bang, total darkness permeated the cosmos.

Then came the first generation of stars, the brilliant and short-lived ancestors of our Sun and its kind, which burnt through the dense fog of primordial hydrogen and helium atoms. Investigating how these first stars ushered in the cosmic dawn and made possible all else that followed — including human life on Earth some 14 billion years later — is one of the hottest research frontiers in cosmology today.

Hiding in the first billion years

In the beginning, there were no atoms, only a dense, hot soup of electrons, protons, and other elementary particles moving around and scattering light at all wavelengths. As the infant universe expanded and cooled below a few thousand Kelvin, protons could hold on to electrons to make neutral atoms of hydrogen and helium for the first time. The cosmic microwave background — the relic glow of the hot, early universe — carries the imprint of cosmic structures at the time of this transition, 380,000 years after the Big Bang. That etching is remarkably smooth, with density variations of only 1 part in 100,000.

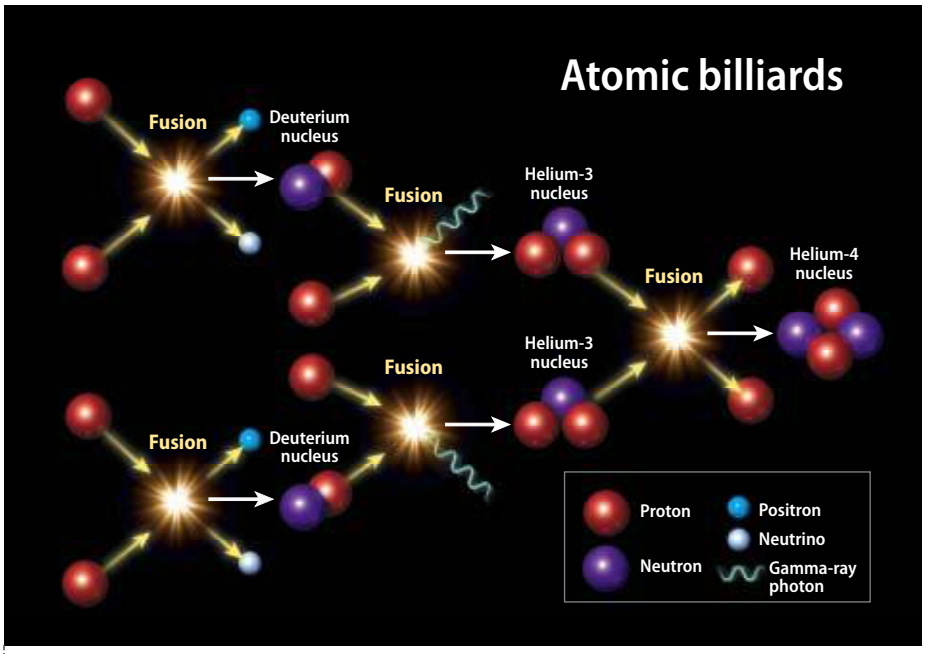
Cosmologists now use sophisticated computer simulations and deep observations with giant telescopes to unravel the tale of how the first stars and galaxies grew out of those tiny ripples. It's a story shrouded in darkness, literally. Between the time neutral atoms formed and the moment the first stars lit up, the universe was in its so-called Dark Ages. Thus, there's little chance for us to see directly the buildup of the first objects. Instead, we have to rely on theory to guide us.

Using sufficiently powerful telescopes, we can expect to see the effects of those first stars on their environment and their immediate descendants — and, in turn, test the theoretical

Ray Jayawardhana, *a professor of astronomy and astrophysics at the University of Toronto, studies the formation of planets, brown dwarfs, and stars.*

stars

THE FIRST STARS FORMED from the universe's primordial material: almost all hydrogen and helium gas, with trace amounts of lithium gas. Because these stars were massive, they lived fast and died young, just 2 million years after their births. LYNETTE COOK FOR *ASTRONOMY*



STARS SHINE as a result of energy released during nuclear reactions. The simplest reaction — nuclear fusion — combines, or fuses, hydrogen nuclei together to produce helium and neutrinos. As a result, energy is released. Extremely high temperatures are required to combine nuclei. The universe's primordial material was mostly hydrogen and helium nuclei. Once the gas collapsed enough because of gravity, nuclei were both hot enough and close enough to fuse. And then there was light: The first star lit up. *ASTRONOMY:* ROEN KELLY

predictions. We have observed some galaxies and quasars shining brightly a billion years after the Big Bang, so the first stars must have formed sometime earlier.

Making the first stars

It may seem futile to try to figure out the birth of the first stars in the distant, unobservable past, when our understanding of present-day star formation is far from complete. But, in some ways, the recipe was simpler back then. We don't need to include the complicating influences of magnetic fields threading gas clouds or shocks from nearby supernovae in the prescription for the very first stars.

The only ingredients in the mix were hydrogen, helium, and traces of deuterium and lithium — plus "dark matter." Dark matter accounts for over 80 percent of matter in the universe, and its influence is felt primarily through gravity. And one doesn't need to worry about the cooling effects of heavier elements or dust produced by previous generations of stars.

In recent years, astronomers have set up elaborate computer codes to model the formation of the first stars. Perhaps the most detailed simulations are those done by Tom Abel of Stanford University, Greg Bryan of Columbia University, and Michael Norman of the University of California, San Diego (see "The universe's first light" on page 22). Another group, including Volker Bromm of the University of Texas, Austin, and Yale University's Richard Larson and Paolo Coppi, has done simulations using a simpler set of assumptions. However, this team explored a wider range of possibilities.

All of these simulations show that the minuscule density fluctuations — the lumps in the primordial soup — in the early universe acted as seeds for growing gas clouds. These fluctuations became the nodes of a network of filaments along which more gas continued to flow in. These clouds contracted under their own gravity and heated up to over 1,000 Kelvin.

A small number of hydrogen atoms paired up to become hydrogen molecules, which helped cool the gas by emitting infrared radiation. Once temperatures in the densest regions dropped to a few hundred Kelvin, the cloud clumps could contract further. Cooling was crucial: It allowed ordinary matter, which cooled by emitting radiation and, therefore, continued contracting, to separate from dark matter. The dark matter didn't cool and, thus, remained scattered throughout the cloud.

Some of the densest gas clumps collapsed until they lit up. Because cooling by small numbers of hydrogen molecules isn't very efficient, these star-forming clumps were much warmer than their counterparts today. (Dust grains and other molecules cool present-day clouds more efficiently.) The gas clumps also had to be more massive in order for gravity to overcome the outward pressure from the hotter gas. This means the first star-forming clumps were probably several hundred times more massive than the Sun.

Did all of that mass go into a single star? Even the most-detailed simulations do not show any tendency for these clumps to fragment as they contract. Thus, theorists think the first stars were rather massive and luminous: Estimates for the upper mass limit range from about 300 to 1,000 solar masses, and the luminosities could have been millions of times that of the Sun.

The cosmic dawn

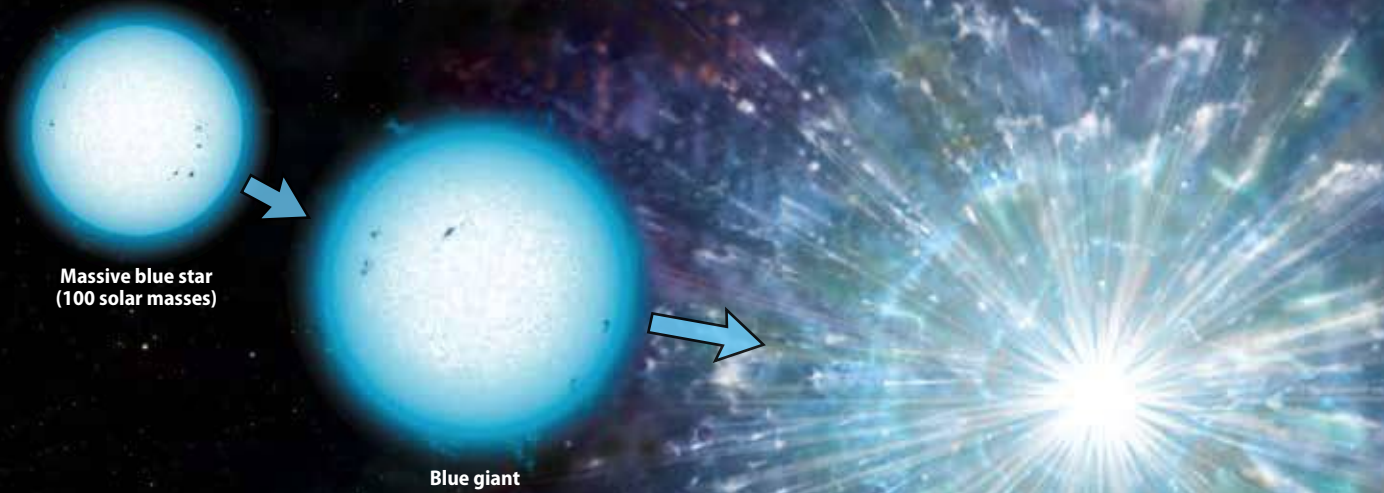
The birth of these first-generation stars marked the cosmic dawn. These behemoths were also extremely hot, with surface temperatures approaching 20 times the Sun's. They emitted primarily ultraviolet light. Their energetic radiation would have started to heat and ionize the neutral hydrogen atoms in their vicinity, carving out a growing bubble of ionized gas around each one. As more and more stars formed over hundreds of millions of years, these bubbles would have overlapped, until nearly all the universe's gas became ionized.

THE FIRST STARS' EJECTA polluted surrounding gas with ingredients for dust, planets, and even life.

Most of the first stars probably ended their brief, but brilliant, lives as exploding supernovae within a few million years. Theory predicts stars with masses between 140 and 260 times that of the Sun blow up completely, expelling the heavier elements they produce through nuclear fusion. The first stars' ejecta seeded surrounding gas with ingredients for dust, planets, and even life, and were eventually incorporated into future generations of stars.

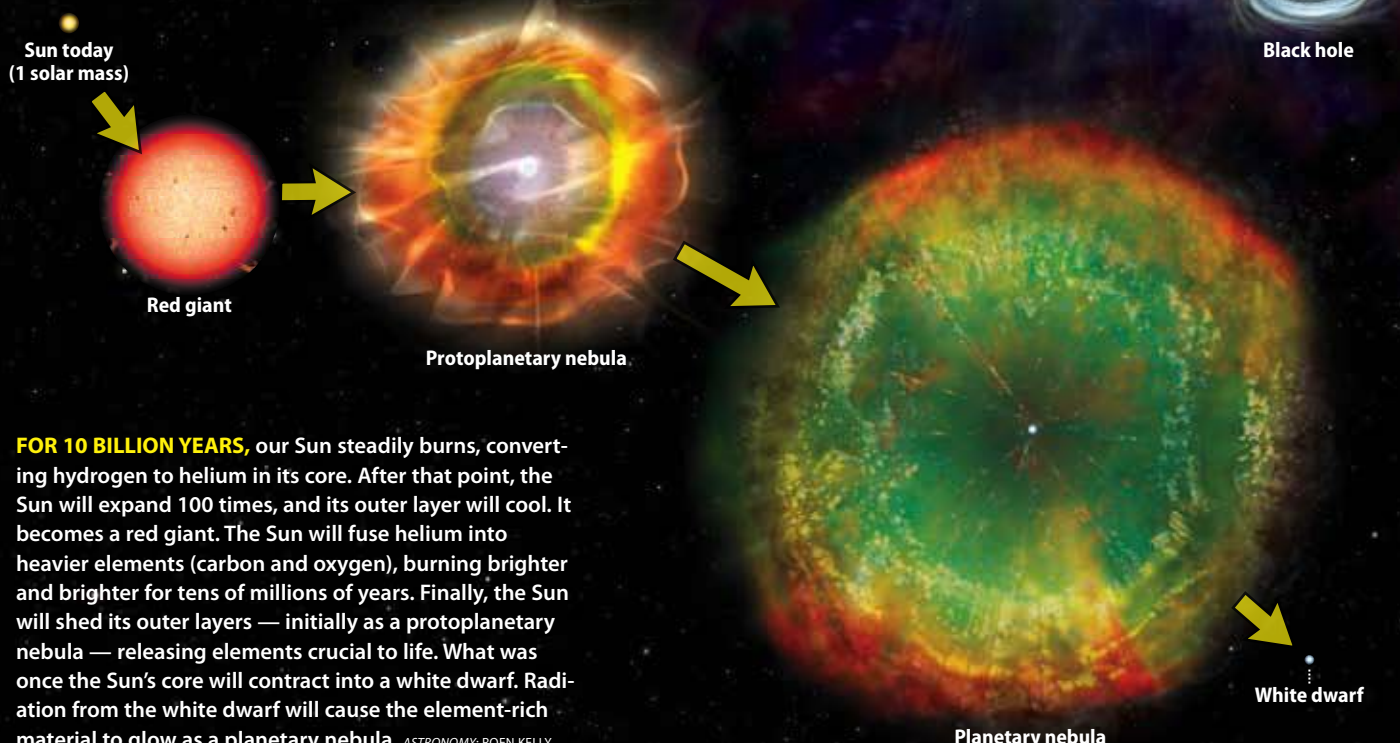
The first stars and their descendants

First star



ONE OF THE FIRST STARS would have been extremely massive — 100 solar masses in this example — formed mostly from hydrogen, helium, and a tiny amount of lithium gas. After just a few million years, the star burned its fuel and ended in fantastic style: as a huge explosion. The star's material — including heavy elements — was ejected. Either its core collapsed as the first black hole, or the explosion was powerful enough to blow up completely and scatter the star's material throughout space.

Sun

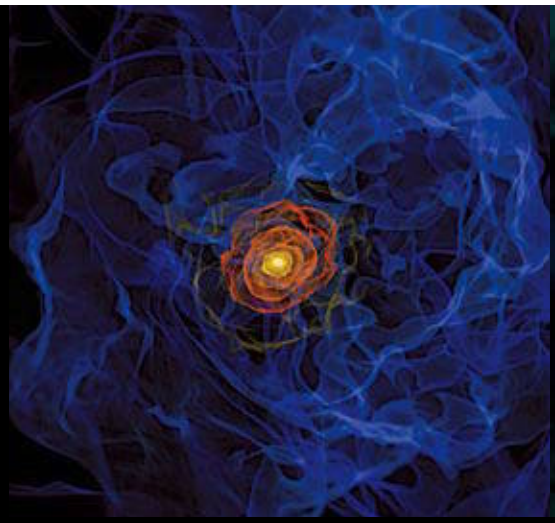


FOR 10 BILLION YEARS, our Sun steadily burns, converting hydrogen to helium in its core. After that point, the Sun will expand 100 times, and its outer layer will cool. It becomes a red giant. The Sun will fuse helium into heavier elements (carbon and oxygen), burning brighter and brighter for tens of millions of years. Finally, the Sun will shed its outer layers — initially as a protoplanetary nebula — releasing elements crucial to life. What was once the Sun's core will contract into a white dwarf. Radiation from the white dwarf will cause the element-rich material to glow as a planetary nebula. *ASTRONOMY:* ROEN KELLY

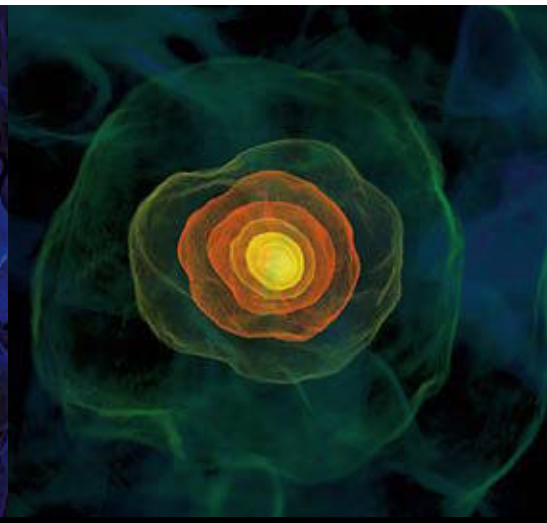
The universe's first light

THE FIRST STAR to form was massive — between 30 and 300 solar masses — and sat inside the first forming protogalaxy, as shown by Tom Abel, Greg Bryan, and Michael Norman in their computer simulations. Hydrogen and helium gas — the universe's primordial material — contracted to form the earliest generation of stars. These huge stars burned bright, lived fast, and died young — after just a 2-million-year life cycle.

VISUALIZATION: RALF KÄHLER AND TOM ABEL
SIMULATION: TOM ABEL, GREG BRYAN, MICHAEL NORMAN



At 65 light-years (20 parsecs) across, this shows cold gas in the center of one of the first protogalaxies.



Follow the contours to zoom inside clumps of different gas densities. One star will form in the center, where the density is highest.

ASTROSPEAK

DARK AGES
The roughly 200,000 years after the cosmic microwave background radiation was released, but before the first luminous sources (stars) turned on.

DEUTERIUM
An isotope of hydrogen whose nucleus is composed of one neutron and one proton (compared to hydrogen, which has no neutrons), nicknamed "heavy hydrogen"; has twice the mass of hydrogen.

QUASAR
(Abbreviated from "quasi-stellar object") the most luminous objects in the universe; thought to be powered by supermassive black holes; lie extremely far away.

REDSHIFT
As the universe expands, light's wavelength is stretched and its apparent color becomes redder; used as a measure of cosmological distance with the symbol z; today is z = 0.

SUPERNOVA
Explosive death of a star at least 8 times the mass of our Sun; expels elements into space that eventually seed planets and life.

Both above and below this mass range, dying massive stars are expected to collapse into black holes without ejecting much of their mass. These stars didn't enrich their progeny by much. But their remnant black holes may have lit up as "mini-quasars" as they accreted surrounding material, providing additional sources of light and ionizing radiation that ended the Dark Ages.

Some of the stellar corpses may have merged with one another to build up the cores that seeded protogalaxies. This could explain why supermassive black holes appear to lurk in the centers of quasars and many galaxies. Thus, the demise of the first stars was perhaps even more important than their birth to all that came afterwards.

There is little chance of catching the first stars in their spectacular death throes, even with today's largest telescopes. But some of them may have given rise to gamma-ray bursts, which are much more luminous than supernovae, at the edge of the observable universe. Detecting such a distant gamma-ray burst is our best hope for probing the end of the Dark Ages directly.

From an ancient era

In the meantime, other ways to investigate those early days exist: by looking for the effects of those first stars on their surroundings. In 2001, a group of astronomers led by Robert Becker of the University of California, Davis, detected possible signs of the final stages of cosmic reionization.

In the spectrum of one of the most distant quasars known, dating to about 900 million years after the Big Bang (at a redshift of 6.4), they found a telltale signature of neutral gas: Essentially, all of the quasar's ultraviolet light had been absorbed by hydrogen atoms in the line of sight.

Slightly closer quasars do not show such complete absorption. These findings suggest the last patches of neutral hydrogen gas were ionized around that time.

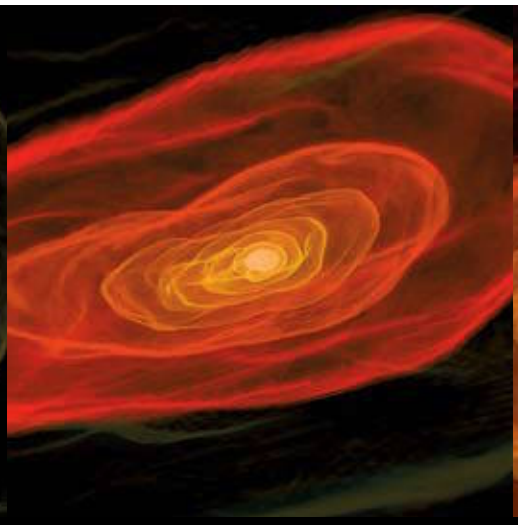
There has been a new twist. Preliminary measurements of the degree of polarization in the cosmic background by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) satellite indicate the universe was reionized much earlier — sometime between 200 and 500 million years after the Big Bang (at a redshift of 10–20), rather than at 900 million years, as implied by the quasar observations. These findings may show the two ends of the reionization period: one the beginning, and one the end.

The apparent discrepancy between the WMAP and quasar results remains "a genuine big puzzle, and no one knows the physical mechanism that can explain such an extended reionization history," says Zoltan Haiman of Columbia University. The answer may come from the European Space Agency's Planck satellite, to be launched in 2007, which will make more reliable measurements of polarization in the cosmic microwave background.

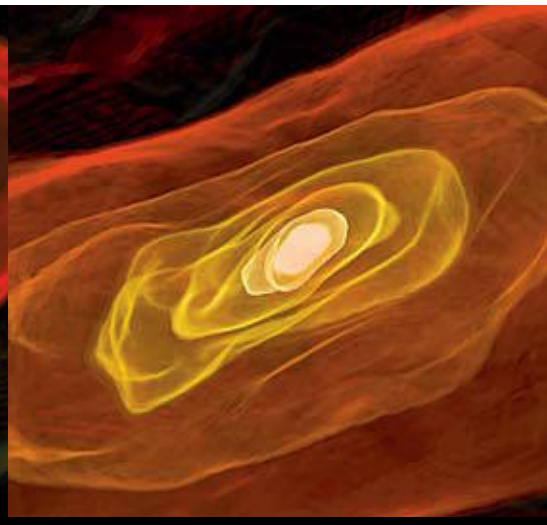
Finding different methods

Astronomers would like to find other, perhaps even more distant, quasars and galaxies that could contain the second generation

The gas density rises rapidly as the primordial gas radiates and collapses faster and faster.



At the center of the protogalaxy, where the gas density is greatest, material continues to collapse into a star.



The white-hot first star — roughly 10 times our solar system's width — burns quickly because of its massive size.

of stars. Simulations predict these protogalaxies would be small and relatively faint.

Several surveys have been undertaken recently, using the Japanese-built Subaru Telescope in Hawaii and the European Southern Observatory's Very Large Telescope in Chile, to look for such objects. A network of radio dishes now being built in northern Chile — the Atacama Large Millimeter Array — will search for distant star-forming galaxies at millimeter wavelengths.

The observers have come up empty so far. Unless they get lucky, success may have to await the launch of the James Webb Space Telescope, the planned successor to Hubble, or the construction of a 20- or 30-meter optical telescope on the ground.

Directly detecting neutral hydrogen is another way to probe the reionization era. Hydrogen atoms emit photons at a characteristic wavelength of 21 centimeters, in the radio. This radiation from the early universe would be redshifted to longer wavelengths — a few meters — by the time it reaches us.

Several new radio observatories are planned for the near future to look for hydrogen's signature. The LOw-Frequency ARray (LOFAR), with 15,000 antennae spread over 62 miles (100 km), is under construction in the Netherlands, and its prototype is taking data. Ue-Li Pen of the Canadian Institute for Theoretical Astrophysics and his collaborators in the United States and China want to begin searching sooner and at low cost: They are placing thousands of commercially available TV antennae on a remote plateau in China and expect to begin searching for hydrogen emission within the next year.

In our own neighborhood

Other astronomers are searching for clues closer to home. While the first stars lived fast and died young, low-mass stars that formed soon after their deaths may still lurk in the Milky Way's halo. Element abundances in the atmospheres of these old and iron-poor second-generation stars could tell us how their massive progenitors lived and died.

THE DEMISE of the first stars was perhaps even more important than their birth.

Within the past few years, astronomers have identified two such "hyper-metal-poor" (HMP) stars. HE 0107–5240, located in the southern constellation Phoenix, and HE 1327–2326, which lies in Coma Berenices, contain $^{1}/_{200,000}$ and $^{1}/_{300,000}$ of the Sun's iron abundance, respectively. But these iron-deficient stars are enhanced in other (lighter) elements, such as carbon.

This was a surprise. Previous theoretical calculations suggested much iron, but only small amounts of carbon, would be ejected during the death throes of the first stars and incorporated into the next generation. Timothy Beers of Michigan State University describes HMP stars as "scribes" of the early universe. "Their atmospheres retain the memory of the composition of the gas from which they formed," he explains.

To account for the abundance pattern in these two stars, their progenitors must have masses as low as 25 times that of the Sun, according to a new theoretical model by Nobuyuki Iwamoto and his colleagues in Japan. To test this emerging scenario, astronomers now are looking for other examples of ancient, iron-poor stars. It isn't easy to find them because they are dim and usually live in the outskirts of the galaxy.

The Sloan Digital Sky Survey's recent extension includes a search called the Sloan Extension for Galactic Understanding and Evolution (SEGUE). This study will collect spectra of 250,000 stars in the Milky Way through summer 2008, and it may reveal other candidates for HMP stars.

"The SEGUE project will allow us, for the first time to get a 'big picture' of the structure of our Milky Way," says Heidi Newberg of Rensselaer Polytechnic Institute in New York.

Clearly, we haven't unraveled the full story of the cosmic dawn yet. Some missing chapters may be deciphered in the spectra of old stars in the Milky Way's halo. Other parts would be revealed in snapshots from billions of light-years away. And plot twists could emerge as astronomers put the pieces together over the next decade.

Relativity's infinite

If beauty is in the eye of the beholder, it's no wonder scientists leaped to embrace general relativity.

EINSTEIN SHOWED GRAVITY CAN TURN SPACE into a fun-house mirror. But it takes a lot of mass — such as that contained in galaxy cluster Abell 1689 — to make the distortions this obvious. Note how light from background galaxies has been twisted and smeared.

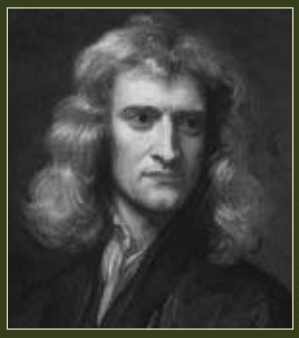
NASA/ESA/THE ACS SCIENCE TEAM

beauty

/// BY JAMES TREFIL

Relativity has always been the

odd man out in the sciences. In the general course of affairs, scientific ideas change slowly. Data challenging the old view start to accumulate, then are debated and worried about until, finally, kicking and screaming, scientists are dragged into a new way of looking at the world. With relativity, though, it was different. A young clerk in the Swiss patent office named Albert Einstein



SIR GODFREY KNELLER

Sir Isaac Newton (1642–1727)

AIP/HEBREW UNIVERSITY/CALTECH ARCHIVES

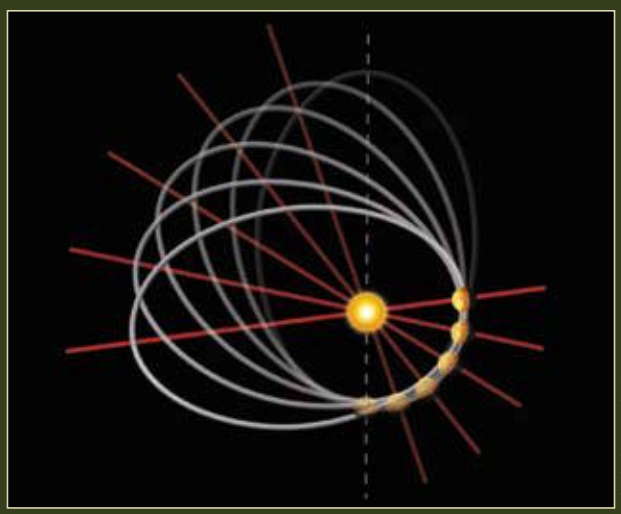
Albert Einstein (1879–1955)

MERCURY'S ODD MOTION

Isaac Newton and Albert Einstein developed the best descriptions of gravity. Newton's law of universal gravitation works in most cases where gravity is not too strong. It was all that was needed to send humans to the Moon and bring them home, and to launch the Voyager 2 spacecraft on a mission to four different planets, using gravity assists from each planet in turn to send it on its way.

Einstein's general relativity comes into play near strong gravitational fields. In the solar system, that means looking in the Sun's vicinity. Relativity's first test came from studies of Mercury's orbit. Newton calculated the inner planet's perihelion, or closest approach to the Sun, should advance about 531" per century. That's based on the gravitational influences from Venus (277"), Jupiter (153"), Earth (90"), and the other planets (10"). Yet Mercury's perihelion actually advances 574" per century.

According to Einstein, Mercury gets a tiny additional push because the force of gravity acting on it is slightly greater than Newton thought. The planet's high-speed orbital motion causes its "effective mass" to increase a little, an effect exacerbated because Mercury moves fastest near perihelion, when the Sun's gravity is strongest. The result: an advance of perihelion 43" per century more than Newton predicted. — *Richard Talcott*



ASTRONOMY: JAY SMITH

THE PERIHELION OF MERCURY, the point in its orbit when it comes closest to the Sun, advances 574" per century, a bit more than Isaac Newton predicted but right in line with Albert Einstein. The advance depicted here is exaggerated to show detail — each "orbit" illustrates how far Mercury's perihelion advances in 12,500 years.

published a paper that was mainly about philosophy. When it appeared, scientists dispensed with their usual arguments about data and took the new ideas to heart.

A big reason for that reaction comes from the fact that relativity is beautiful. I know that seems a strange word to apply to what is, after all, a mass of equations, but that's the way physicists perceive it. The beauty stems from the central principle of Einstein's work called, appropriately enough, the principle of relativity. It says that any two observers, no matter where they are or how they are moving, will see the laws of nature operating the same way. The universe, in other words, doesn't care how it's being observed — it's the same for everybody.

Here's an example to help you think about this: A friend rides by in a car and, as he passes you, he throws a ball straight up in the air. To your friend in the car, the ball travels vertically up and then down. To you, the ball travels in an arc because the car moves while the ball glides through the air. The descriptions you and your friend give are different — each description is *relative* to the observer's location. On the other hand, if you each describe the laws of nature that made the ball do what it did from your point of view, you both would give the same answer, citing things like Newton's law of universal gravitation. Descriptions of events are relative to the observer — the laws of nature are not. (By the way, Einstein never liked the name theory of relativity for his brainchild. He wanted to call it the theory of invariants.)

Einstein worked out the consequences of this simple idea in two papers. In 1905, he published the results for the case where different observers are moving at constant (but different) speeds. This is called special relativity. Most of the strange things associated with relativity — moving clocks slowing down, moving objects getting more massive, and so on — come from this work. From a mathematical point of view, this is relatively simple stuff — the kind of material often taught to freshman physics majors.

Stepping on the gas

Extending the idea to all observers, even those who are accelerating, turned out to be a far more difficult proposition mathematically. The fact that it took Einstein — possibly the greatest mathematical physicist the world has known — until 1916 to straighten things out and publish this part of the theory should tell you all you need to know. The result of this work, called general relativity, remains our best theory of gravitation today.

So how does gravity get into it? Anyone who has felt heavier momentarily when an elevator starts climbing, or has been pushed back into the seat as a plane starts its takeoff, has experienced the answer. Einstein realized someone standing on a scale in an ascending elevator would see her weight increase, just as if the planet on which she was standing had suddenly grown more massive. To Einstein, this

James Trefil *is the Clarence J. Robinson Professor of Physics at George Mason University in Fairfax, Virginia. His latest book is* Human Nature: A Blueprint for Managing the Planet — by People, for People *(Henry Holt & Company, 2005).*

meant someone on Earth's surface feels the same force as someone in a spaceship accelerating fast enough to produce an equivalent effect. As in special relativity, both people would see the same natural laws operating, except this time, gravity appears as just another effect of our choice of reference frame. This connection between frames of reference (like the accelerating elevator) and mass (which generates gravity) is the crux of general relativity. In Einstein's language, gravity becomes just an effect of geometry.

It's one thing to propose a theory like this, as beautiful as it may be, and something else to show that it makes predictions in line with experimental results. And here's where the anomaly I talked about earlier comes in. The Newtonian picture of the universe works extraordinarily well for most things we see. It was all scientists needed, for example, to guide the Cassini spacecraft to Saturn. The reason: Under most ordinary situations, the predictions of Newtonian gravity and Einstein's theory differ by so little that experiments can't differentiate between them. It's only in extreme situations — the vicinity of a black hole, for example, or the early stages of the Big Bang — that the two theories give really different results.

When physicists seek ways to validate Einstein's ideas — something that has to be done no matter how beautiful they are — we find a surprising dearth of possible tests. Until recently, in fact, there were only three. Although relativity passed these tests with flying colors, three experiments isn't a great foundation for what ranks as one of the most revolutionary ideas in modern science. Let's recap those classical tests.

Mercury on the loose

The first verification of general relativity wasn't so much a new test as an explanation of an old puzzle. For centuries, astronomers have known every planet orbits the Sun on an elliptical path. One point on each orbit, called perihelion, marks the planet's closest approach to the Sun. If only one planet circled the Sun, that point would be the same every time the planet came around its orbit. The gravitational pull of other planets, however, causes the point to move ahead a little each time the planet swings around. Astronomers call this effect the advance of the perihelion. It shows up most easily with Mercury, whose perihelion advances a little less than 600" (about one-sixth of a degree) per century — a small number by any measure.

When you account for everything that should affect the orbit of Mercury in the Newtonian picture, however, you come up about 43" per century short of explaining the planet's observed perihelion shift. Einstein pointed out that general relativity, which changes the force of gravity ever so slightly from its Newtonian form, could explain this tiny discrepancy. This was a triumph for the new theory. Since then, astronomers have used advanced radar-ranging techniques to measure accurately the perihelion shift of all the inner planets (including Earth), and the theory has come through each time. Score one for Einstein.

The most dramatic confirmation of general relativity occurred during the total solar eclipse of May 29, 1919.

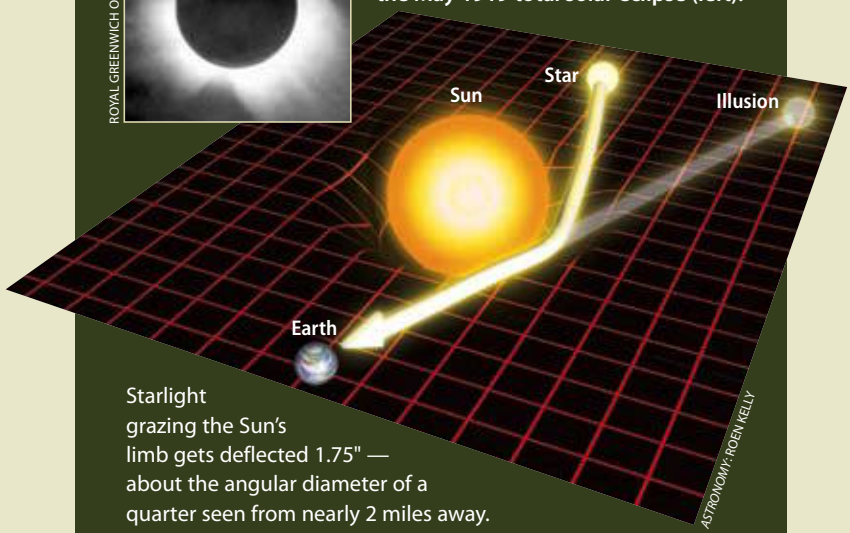
STARLIGHT'S LONG, STRANGE TRIP

Geometry rules in general relativity because the theory treats gravity as a manifestation of space-time curvature. Matter warps space-time, and whenever an object encounters that warpage, its path is deflected. That holds whether the object is a planet orbiting the Sun or a photon of light passing a massive object.

Observations of total solar eclipses provided an early test of general relativity. Scientists photographed the positions of stars near the Sun's limb during totality, and then compared them with the same star field on photos taken at night. As in most relativity experiments made in the solar system, the effect is subtle.

ROYAL GREENWICH OBSERVATORY

THE SUN warps space-time, deflecting starlight passing the solar limb (below). This effect was first observed during the May 1919 total solar eclipse (left).

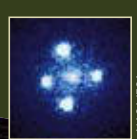


ASTRONOMY: ROEN KELLY

Starlight grazing the Sun's limb gets deflected 1.75" — about the angular diameter of a quarter seen from nearly 2 miles away.

The Sun is only a middling star, however. If the deflecting body is a galaxy or galaxy cluster, the effect can be spectacular. The body acts like a lens, magnifying and distorting the light of more distant objects. In the Einstein Cross (below right), a massive galaxy 400 million light-years from Earth forms four images of a single quasar located 8 billion light-years away. In the galaxy cluster Abell 2218 (left), the light from even more distant galaxies gets distorted into long, colorful arcs. — *R. T.*

NASA/ESA/J.-P. KNEIB/R. ELLIS



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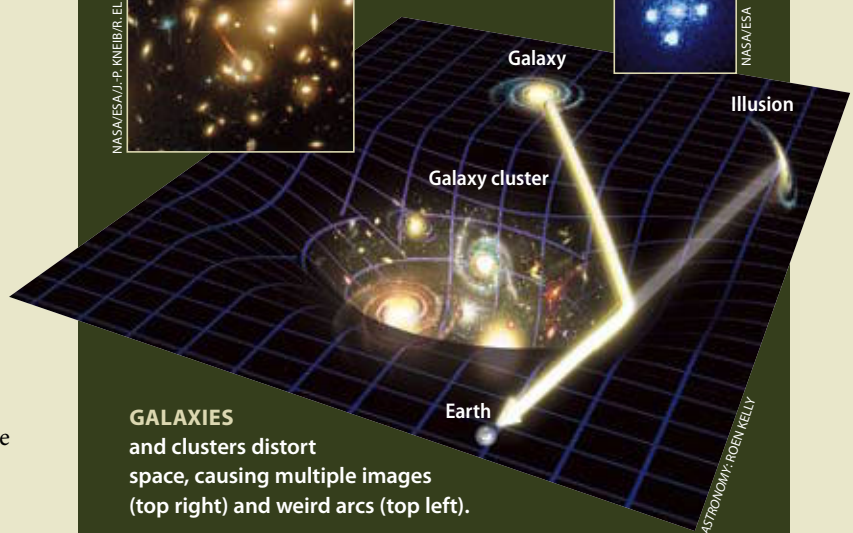
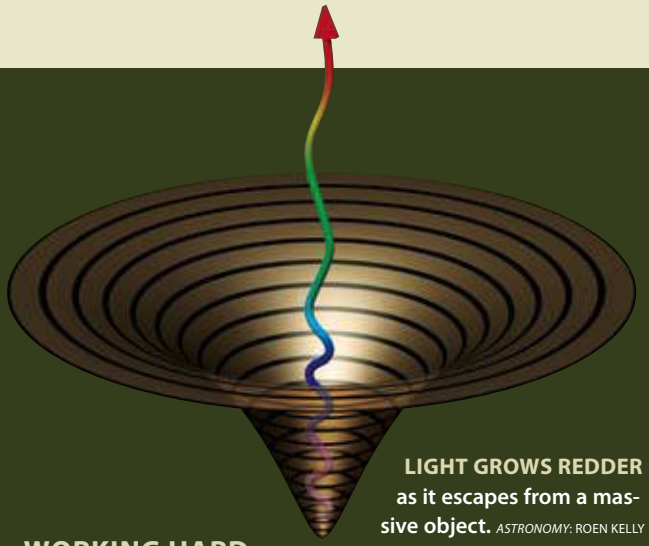


ASTRONOMY: ROEN KELLY

GALAXIES and clusters distort space, causing multiple images (top right) and weird arcs (top left).



LIGHT GROWS REDDER as it escapes from a massive object. *ASTRONOMY:* ROEN KELLY

WORKING HARD AGAINST GRAVITY'S CLUTCHES

Gravity affects light in many ways. The most famous effect is the deflection of starlight as it passes a massive object (see "Starlight's long, strange trip," page 27). But gravity produces another effect that changes the wavelength of light.

To understand gravitational redshift, it helps to use a technique Einstein found useful: a thought experiment. Imagine an elevator with a laser on the floor and a detector on the ceiling. If the elevator floats in space, far from any gravitational field, and you shoot a laser beam from floor to ceiling, the detector should record the same wavelength of light as the laser emitted.

Now imagine you're in the same elevator but are free-falling in Earth's gravitational field. Between the time the laser emits light and it reaches the ceiling, the receiver approaches the source. This should cause a Doppler shift to shorter, bluer, wavelengths. Yet an observed blueshift would violate Einstein's belief that the laws of nature would be the same in both elevators. So, light moving against gravity has to be redshifted to compensate.

The gravitational redshift has been seen in laboratories and in the Sun's light. But stronger gravity produces a greater effect. Light from the white dwarf Sirius B shows a redshift equivalent to the star moving away from Earth at 200,000 mph. — *R. T.*

JOHN CHUMACK

BRILLIANT SIRIUS shields a white-dwarf companion astronomers used to measure gravitational redshift.

Einstein's theory predicts that when light passes near a massive object like the Sun, its path bends. To an observer on the opposite side of the Sun, it would look as though the light were coming from a slightly different direction and, therefore, the position of the object had shifted.

Most of the time starlight passes near the Sun, the Sun's brilliance overwhelms it. During a total solar eclipse, however, the Moon blocks the brightest part of the Sun from view, so light from distant stars passing near the solar surface can be detected. To test general relativity's prediction, 6 months before the 1919 eclipse, astronomers photographed the star field destined to lie on the edge of the eclipsed Sun. The stars were high in the night sky and easy to see. During the eclipse, scientists shot the same star field and checked the apparent star positions.

British astronomer Sir Arthur Eddington led one eclipse expedition to Príncipe Island off the coast of Africa. When he announced the stars' positions matched Einstein's predictions, the scientific community, who wanted to believe the theory anyway, jumped on the general-relativity bandwagon. Today, radio astronomers routinely record radio waves from distant quasars as the waves skim the Sun's surface, and the measured displacement of the waves always matches the theory's predictions. Score two for Einstein.

Another phenomenon associated with Eddington's measurement, however, has puzzled me (and many other scientists): the almost instantaneous elevation of Einstein to a major figure in pop culture. Characters modeled after Einstein — kindly, pipe-smoking, white-haired scientists — routinely appeared in movies from the 1920s to 1950s. Even today, a half century after Einstein's death, you can walk into a college bookstore and see him on posters, right next to other icons of the mid-20th century like Marilyn Monroe and James Dean. Understanding why this happened constitutes, in my mind at least, a question in the social sciences nearly as profound as the questions physicists ask about the nature of gravity.

Out of a gravity well

The third classical test of relativity came from the theory's prediction that light moving upward in a gravitational field (think of a flashlight beam directed into the night sky) would have its wavelength shifted slightly to the red. In essence, the light loses energy as it climbs out of the field. One of the early applications of laser technology was to verify this prediction in 1959.

Astronomers also have helped verify the gravitational redshift, although not as precisely as laboratory experiments. Light climbing out of a star's gravitational field should be redshifted more than in the laboratory. For the Sun, the effect amounts to an increase in wavelength of less than two parts per million. But with the much stronger gravity at a white dwarf's surface, the effect is nearly 50 times larger. Observations of white dwarfs show the redshift matches Einstein's predictions to within about 20 percent.

So there you have it. Until the 1980s, this was all general relativity had to hang its hat on. It's a surprisingly thin list for such a powerful new idea.

The last couple of decades have seen a flood of new tests: some completed, some proposed, and some ongoing. It's not that modern scientists have improved on the theory or performed new calculations. It's just that, as so often happens in the history of science, a lot of ordinary lab work gradually has improved our ability to measure things. Tests beyond our reach a few decades ago now can be done, or at least contemplated. Look at it this way: If both Newton's and Einstein's predictions about a certain number are identical for seven decimal places; if you can measure that quantity to eight decimal places, you can see which theory is right. Basically, that's how scientists have tried to verify general relativity during the past 2 decades.

Scientists recognize three broad classes of general-relativity tests. Some are straightforward attempts to confirm predictions of the theory — "Relativity says X will happen, so let's measure X." Another class begins with a prediction of some effect but is motivated more by the desire to discover new things about the universe. In this case, relativity is just a side issue. Finally, and most interesting to me, comes the class of experiments in which tests of general relativity are inadvertent. The theory gets tested, but only in the context of some larger engineering endeavor.

Probing gravity

In April 2004, an extraordinary event in the history of general relativity took place when an experiment called Gravity Probe B was launched from Vandenberg Air Force Base, California. I call this event extraordinary for several reasons, not the least of which is that scientists prepared for it longer than any scientific experiment I know.

When I was a graduate student at Stanford University in the 1960s, I met a young English postdoctoral fellow named Francis Everitt. Sporting a fashionable '60s ponytail, he was planning a major test of general relativity. Today, the ponytail is gray, the postdoc is a senior professor, and the experiment is finally operating.

The easiest way to think about Gravity Probe B is to picture an ordinary toy top. The top spins around its axis, but the axis also executes a lazy circle. The forces exerted on the top's point by the floor coupled with gravity cause the latter effect, known as precession. Most spinning objects show precession. Earth's axis, for example, goes through one precessional cycle every 26,000 years, caused by the gravitational tugs of other solar system bodies acting on Earth's equatorial bulge.

The Gravity Probe B experiment employs the world's four most-precise gyroscopes (think of them as high-tech tops) mounted in a satellite, with the aim of measuring their precession. General relativity predicts a small precession due to Earth's gravitational effects and the satellite's orbital motion. It's taken a long time for Gravity Probe B to fly because scientists had to overcome a number of technical hurdles for such a precision experiment to work, not to mention putting it into a rocket's nose cone and shooting it into space.

The gyroscopes — spinning 400 miles (640 kilometers) above Earth as you read this — are spheres made so precisely they have been called the world's roundest objects. Blow up

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = 8\pi T_{\mu\nu} - \Lambda g_{\mu\nu}$$

EINSTEIN'S FIELD EQUATION may look simple, but enter at your own risk. The equation is the basis of general relativity.

EINSTEIN LOOKS TO THE COSMOS

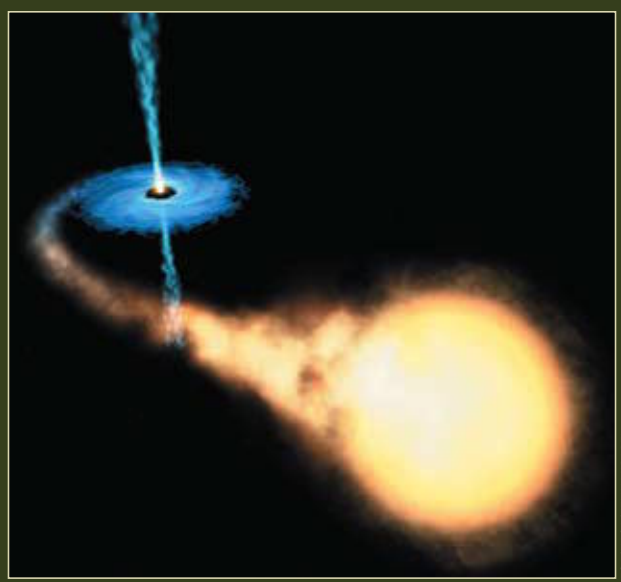
Einstein's field equation includes mathematical expressions known as tensors. The equation tells how matter and energy (represented by the stress-energy tensor, $T_{\mu\nu}$) warps space-time (represented by the metric tensor, $g_{\mu\nu}$).

The innocuous-looking Λ in the last term is the cosmological constant. The permanence of the universe was a firm belief in Western philosophy when Einstein developed relativity, and he was unwilling to give it up. The original field equation told him the cosmos must be evolving, so he modified the equation to keep the universe static. When he learned the universe is expanding, he called the constant "my greatest blunder."

But perhaps he was too hasty again. Observations of distant supernovae now show the expansion of the universe is accelerating. A cosmological constant could be one explanation. If so, this could be a rare instance when two wrongs do make a right.

General relativity quickly became cosmologists' prime tool. The first new cosmological model came in 1917 from Dutch astronomer Willem de Sitter. In the 1920s, both Russian mathematician Alexander Friedmann and Belgian astronomer Georges Lemaître developed other models. Lemaître first hypothesized the universe might have begun with a Big Bang.

General relativity also predicted black holes — objects with gravity so strong not even light can escape. In 1939, American physicists Robert Oppenheimer and Hartland Snyder published the first description of black holes based on relativity. At the time, most scientists (including Einstein) didn't think these beasts existed. But astronomers find them in binary systems, where a stellar-mass black hole swallows gas from a companion; and in active galaxies and quasars, where supermassive black holes drive the most energetic objects in the universe. — *R. T.*



ESA/NASA/FELIX MIRABEL

A BLACK HOLE — one of general relativity's strangest predictions — swallows matter from a companion star.

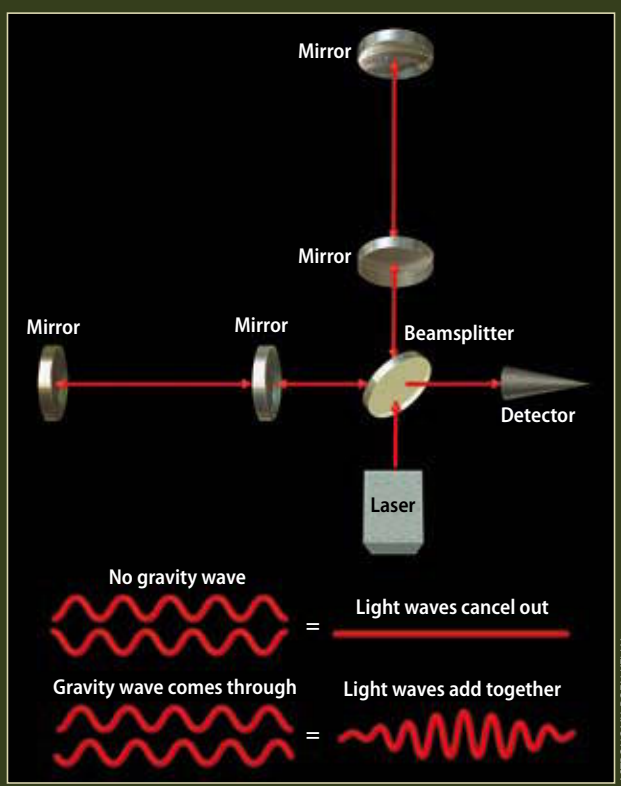
LIGO LABORATORY

THE LASER INTERFEROMETER GRAVITATIONAL-WAVE Observatory (LIGO) consists of two sites, this one in Hanford, Washington, and one in Livingston, Louisiana.

CATCHING THE PERFECT WAVE

If the Sun ceased to exist this instant, it would take 8 minutes for the sky to darken — the length of time it takes light to reach Earth from the Sun. Would we fly off into space before then? No. Special relativity says information can't travel faster than the speed of light. We'd remain unaware for the same 8 minutes.

Although mundane events like the Sun's death create ripples in the fabric of space-time, general relativity tells us bigger events — like a supernova or the collision of two black holes — trigger greater disturbances. Those are the kinds of events LIGO is searching for (see "Riding a wave" at right). But scientists already have detected gravitational waves indirectly. Observations of a binary pulsar, in which two neutron stars orbit each other, show the system loses energy by radiating gravitational waves at just the rate relativity predicts. Americans Russell Hulse and Joseph Taylor won the 1993 Nobel Prize in physics for their study of the binary pulsar. — *R. T.*



ASTRONOMY: ROEN KELLY

EACH LIGO SITE houses lasers and mirrored test masses that detect gravitational waves by looking for light interference.

the ping-pong-ball-size quartz spheres to the size of Earth, and the tallest "mountain" would be less than 3 feet high. Scientists estimate that, within the next year, we'll know whether general relativity has passed this test.

Relativity also predicts that when a massive object moves, it creates waves in space, much as your hand creates waves when you move it through water. These so-called gravitational waves are weak, but general relativity says they ought to be there. And just as waves on the water make a cork bob up and down, gravitational waves stretch and distort massive objects. A gravitational wave hitting a basketball, for example, will stretch it sideways, let it snap back, then stretch it up and down, before letting it go back to its original configuration. This stretch is small — a gravitational wave hitting your car, for example, will distort its shape by about the length of the nucleus of a single atom. Scientists have long tried, unsuccessfully, to detect these waves using ever-more-refined apparatus.

Riding a wave

Enter LIGO: the Laser Interferometer Gravitational-wave Observatory. This mammoth project uses equipment at two separate sites, one in Louisiana and one in Washington state, to try to detect the presence of gravitational waves. LIGO construction was finished in 1999, and initial operations began in 2001. Currently, the observatory is close to reaching its design sensitivity.

At the heart of each installation is a huge L-shape vacuum pipe; each arm of the L is 2.5 miles (4 km) long. A test mass outfitted with mirrors at the end of each arm is free to move in response to passing gravitational waves. Think of them as two pieces on the surface of a "basketball" 2.5 miles in diameter. Laser beams running through the vacuum pipe precisely monitor the positions of the masses, which will move far less than the diameter of a single atom when a wave passes. Having two installations provides a check against a local disturbance — micro-earthquakes or other sudden vibrations, for example, or fluctuations in the lasers themselves — being mistaken for a gravitational wave.

While LIGO was built to detect the gravitational waves predicted by general relativity, its real purpose is to open a new window on the universe. If LIGO detects gravitational waves that are somehow different from what general relativity predicts, it still will be a success. It will bring us new information about the universe, just as the first radio telescopes did in the 1930s.

Walk into any electronics store, and you can buy your own apparatus to test general relativity. The Global Positioning System (GPS) is an example of what I call an inadvertent test of the theory. The system's main working parts are 24 satellites, each containing a precision atomic clock, orbiting about 14,500 miles (23,300 km) above Earth. By measuring how long it takes signals to travel from several satellites to your location, a GPS receiver calculates your exact location.

Relativity comes into this technology in two places. Because the satellites move briskly in their orbits, their atomic clocks slow down. This is an effect purely of special relativity. In addition, because the satellites orbit so far above

Earth, they lie in a different gravitational field than the surface. In this situation, general relativity predicts the clocks should speed up because of the lower gravity in orbit.

These effects are complicated by the fact that the satellites move toward and away from Earth as they orbit. The system has to correct for all of these effects to produce an accurate position.

I've been told that when the first satellites in the GPS system were built, the engineers so distrusted the unfamiliar effects of relativity, they put in a switch that would allow them to turn the relativistic corrections off if they had to. Needless to say, the switches were never used.

The atomic clocks in the GPS satellites are accurate to 13 decimal places, and you need every one of those decimal places to make the system work. Were the effects of relativity ignored, there would be a cumulative error of about 7 miles (11 km) per day in the position of each satellite in the system. This means every time you turn on your GPS receiver, you perform your own test of the theory, whether you mean to or not.

Back to the future

Even if general relativity meets all the current tests — as most physicists expect it will — that isn't the end of the story. We know the theory has to break down at some point, if only because, in its present form, it does not incorporate the effects of quantum mechanics. (Quantum mechanics describes the universe at tiny scales — it's how physicists understand the behavior of atoms.)

There are other ways general relativity could fail, and scientists are thinking about testing many of them. One intriguing way relativity could falter would be a violation in a basic symmetry built into the theory. Relativity predicts, for example, that rotating a clock in space will not change the rate at which it ticks. If this is false, the concepts of space and time built into the theory would have to change. This is precisely what happens in some theories that attempt to combine quantum mechanics and general relativity.

Whether or not clocks actually speed up or slow down in this way can be tested by watching two neighboring clocks as Earth's rotation changes their positions relative to each other. Experiments at the Harvard-Smithsonian Center for Astrophysics already have shown that, for some clocks, relativity can be trusted out to 31 decimal places. Nevertheless, scientists are planning to run experiments on the International Space Station to compare the rate at which different clocks tick. As the station moves around in its orbit and rotates around its axis, the relative positions of the clocks will change rapidly. If relativity is violated, we should see them go into and out of sync with each other.

So that's where relativity stands as it enters its second century. Thanks to the ingenuity of modern experimenters, general relativity no longer sits in lonely splendor as the only poorly tested major theory in science. From now on, it will have to take part in the rough-and-tumble of skeptical experiments. This, of course, is only fitting because that is the lot of every other scientific theory — whether it was devised by Einstein or not.

GRAVITY PROBE B/STANFORD UNIVERSITY

ALBERT EINSTEIN appears shrunken and flipped as his image passes through one of Gravity Probe B's quartz rotors.

START DRAGGIN' MY FRAME AROUND

Earth is nowhere near as big as the Sun and warps space-time much less. Still, Earth creates a small dimple in the space-time fabric. General relativity predicts that, as Earth rotates, it should twist the local fabric by a minuscule amount. Derived in 1918 by Austrian physicists Joseph Lense and Hans Thirring, this is known as the Lense-Thirring effect, or, more colloquially, frame dragging. This is what Gravity Probe B and its precision gyroscopes are looking for.

Frame dragging should affect any Earth-orbiting satellite. In 2004, researchers Ignazio Ciufolini of the University of Lecce, Italy, and Erricos Pavlis of the Joint Center for Earth Systems Technology in Baltimore announced they had detected frame dragging. They studied the orbits of NASA's Laser Geodynamics Satellite (LAGEOS) and the joint NASA/Italian Space Agency LAGEOS II and found that the plane of the orbits shifted about 6 feet (2 meters) per year — within 1 percent of what relativity predicts. Ciufolini and Pavlis estimate their measurement is accurate to 10 percent. Gravity Probe B should whittle that down to less than 1 percent. — *R. T.*

RUSS LEESE/GRAVITY PROBE B/STANFORD UNIV.; INSET: KATHERINE STEPHENSON/STANFORD/LOCKHEED MARTIN

GRAVITY PROBE B'S number 4 gyro is inspected by Stanford University engineer Chris Gray in August 2000 (above). The spacecraft (inset) was launched in April 2004.

Why you live in a multiverse

Cosmic inflation, string theory, and the cosmological constant all suggest there's more to the universe than the part we can see. /// BY STEVE NADIS

More than 400 years ago, the Dominican monk Giordano Bruno was burned at the stake for making a heretical claim: that our universe is infinite and contains an infinite number of worlds.

Today, cosmologists arguing a similar point — that our universe is but one of many universes comprising a larger "multiverse" — are hoping for a better fate, maybe even a Nobel Prize. There is growing acknowledgement among physicists and astronomers that this idea, outlandish as it sounds, just might be true.

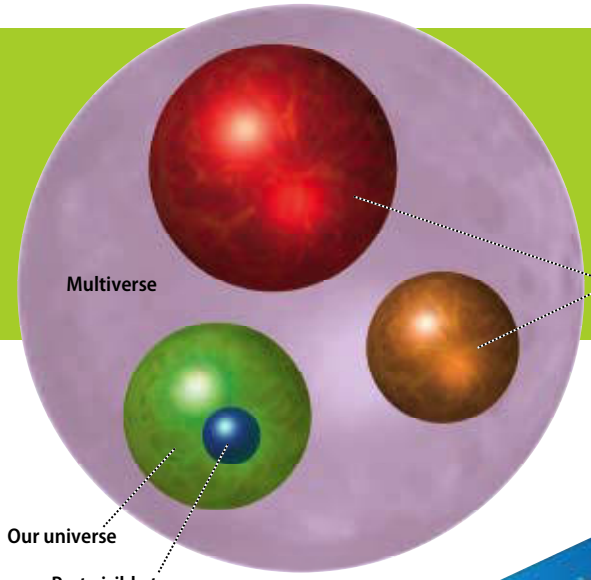
One picture emerging from cosmology, astronomical observations, and particle physics is that there's a lot more to the universe than we can see: The universe is not only vast, extending far beyond the visible portion, it may be composed of distinct, exponentially large regions with wildly divergent features. For all practical purposes, these realms could be regarded as separate universes within an all-embracing multiverse.

While schemes exist for multiple or parallel universes, one promising approach reflects what Harvard physicist Nima Arkani-Hamed calls "the confluence of things now pushing us toward the notion of a multiverse."

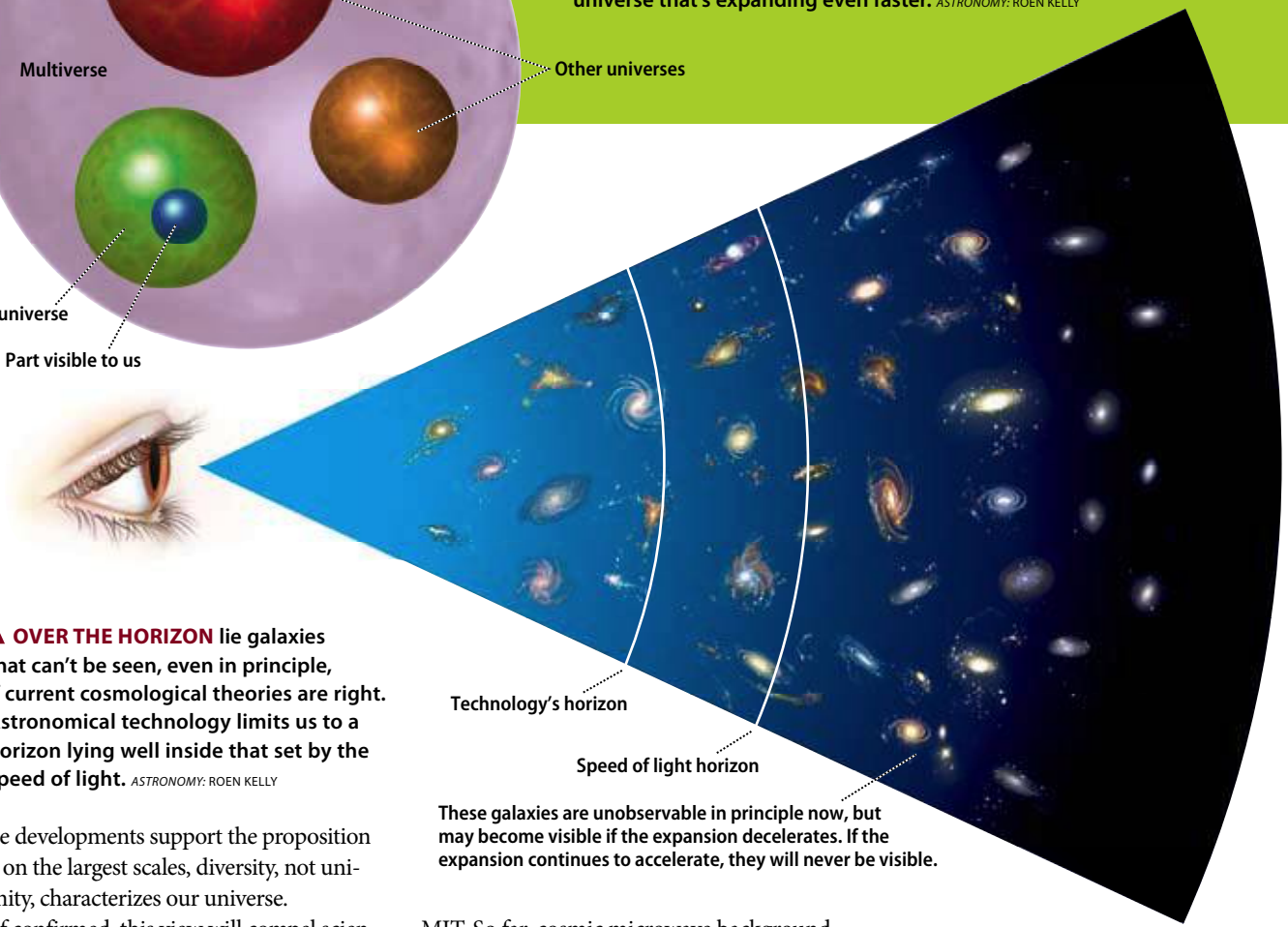
These include: measurements that indicate the universe's expansion is accelerating; empirical tests that bolster the inflationary universe scenario; theories of eternal inflation that suggest an endless number of Big Bangs; and recent developments in string theory that show how to design universes with widely different properties. Collectively,

"I fully expect the true nature of reality to be weird and counterintuitive, which is why I believe these crazy things." —*Max Tegmark*

HOW MANY UNIVERSES are there? Astronomers think the Big Bang may have spawned multiple universes, each like its own bubble, perhaps containing different natural constants and even physical laws. DON DIXON FOR *ASTRONOMY*



◀ **DARK ENERGY will expand our universe, but we will see less and less of this universe as time goes on. The finite speed of light determines how far we can see, but as the visible universe (blue sphere) grows, it is an ever-smaller part of a larger universe that's expanding even faster.** *ASTRONOMY:* ROEN KELLY


Technology's horizon
Speed of light horizon
These galaxies are unobservable in principle now, but may become visible if the expansion decelerates. If the expansion continues to accelerate, they will never be visible.

▲ **OVER THE HORIZON lie galaxies that can't be seen, even in principle, if current cosmological theories are right. Astronomical technology limits us to a horizon lying well inside that set by the speed of light.** *ASTRONOMY:* ROEN KELLY

these developments support the proposition that on the largest scales, diversity, not uniformity, characterizes our universe.

If confirmed, this view will compel scientists to extend the Copernican Revolution, according to Cambridge University's Sir Martin Rees. "We've gone from thinking about different worlds within our universe, to thinking about entirely different universes."

Far horizon in view

Starting on the simplest level, we know the universe stretches far beyond the limits of our telescopes. At present, our "horizon" is about 14 billion light-years (actually about 40 billion light-years, considering that the stuff we've seen has already expanded farther). We call a sphere of that radius a Hubble volume.

Observers 100 billion light-years away would inhabit a completely different Hubble volume than ours, notes Max Tegmark of MIT. So far, cosmic microwave background measurements show the universe to be flat to a precision of about 1 percent. If space is ultimately curved, says Tegmark, its radius of curvature is at least 10 times bigger than the horizon. This means our universe contains at least 1,000 separate Hubble volumes.

According to inflation theory, the universe stays flat forever. In other words, the universe is infinite, and strange things can happen in infinite space. Work by Jaume Garriga of the University of Barcelona and Alexander Vilenkin of Tufts University shows such a universe would have an infinite number of observable universes, or "O-regions." Each of these spatially finite O-regions has a finite number of possible histories. History thus repeats itself, over and over.

"Whenever a thought crosses your mind that some terrible calamity might have happened, you can be sure it has happened in some of the O-regions," Garriga and Vilenkin write. "If you nearly escaped an accident, you were not so lucky in other regions with the same prior history."

Vilenkin finds this somewhat depressing because it suggests we're not special. But he considers the logic airtight: If the total number of possible histories is finite and the number of regions infinite, there's no other conclusion to draw. Tegmark, who received tenure from MIT in 2005, isn't depressed by the prospect of not getting tenure in other universes. Moreover, he actually *believes* this stuff.

"Whenever you go beyond human scales, counterintuitive things should happen, and that's exactly what we've seen in the last century," he says. "If we go very fast, time slows down. If you make a star very massive, eventually you'll get a black hole. If you make something very small, it can be in two places at once. I fully expect the true nature of reality to be weird and counterintuitive, which is why I believe these crazy things."

Steve Nadis, *a frequent* Astronomy *contributor, is never happier than when writing about the weirder aspects of the universe we live in. His home is in Cambridge, Massachusetts.*

"We've gone from thinking about different worlds within our universe, to thinking about entirely different universes." — *Sir Martin Rees*

If you want crazy, consider this: Inflation, the explosive growth spurt that started and stopped before our universe was 10^{-30} second old, never really ended. It stopped in our region, of course, giving rise to the bubble universe (or O-region) we call home. But the process continues unchecked elsewhere, spawning new bubble universes along the way.

Eternality, a feature of almost every inflation model, occurs because inflation is driven by an unstable material (called a false vacuum) that decays over time. But this material expands even faster than it decays, so expansion wins out, and inflation never ends.

Bubble universes

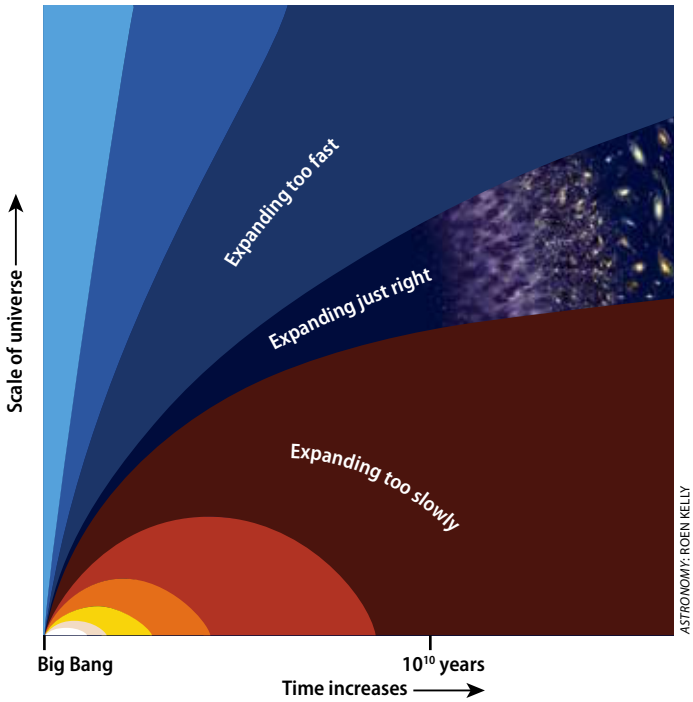
Eternal inflation creates a different kind of universe than the simple sphere we once envisioned. Think of Swiss cheese instead. Each hole represents a bubble universe; the cheese represents the space between the bubbles and is expanding faster than the speed of light. Not only do the bubbles get farther and farther apart, new bubbles keep forming within the cheese — the result of new Big Bangs popping off in a never-ending chain reaction. Eternal inflation doesn't just produce an oversized hunk of cheese; it produces a multiverse.

How convincing is this scenario?

"Many, no doubt, would call it a house of cards, but from my point of view, it looks very plausible," says MIT's Alan Guth, generally credited as inflation's inventor. Inflation has been very successful in making predictions — flatness, homogeneity, and scale invariance — for the part of the universe we can observe, he says, "which means we should also take seriously its predictions for parts of the universe we can't observe."

As scientists, adds Tegmark, "We're not testing the general idea of a multiverse.

OUR COSMIC FATE hangs on the universe getting the parameters right, or nearly so. If the universe expands too fast (scenarios shown in cool colors), stars and galaxies don't form. And if the universe does not expand fast enough (scenarios shown in warm colors), it never cools sufficiently — or there's no time for stars to evolve before everything falls back together in a Big Crunch.



ASTRONOMY: ROEN KELLY

We're testing inflation — a mathematical theory that predicts a multiverse and all kinds of other stuff." Inflation has passed all empirical tests to date, but the idea faces even more rigorous challenges coming later this decade and beyond.

"We still have no idea whether there is one universe or many," says Rees. Yet at a 2003 Stanford University conference, he was confident enough of the multiverse's existence to stake his dog's life. Stanford's Andrei Linde went further, claiming he would put his own life on the line.

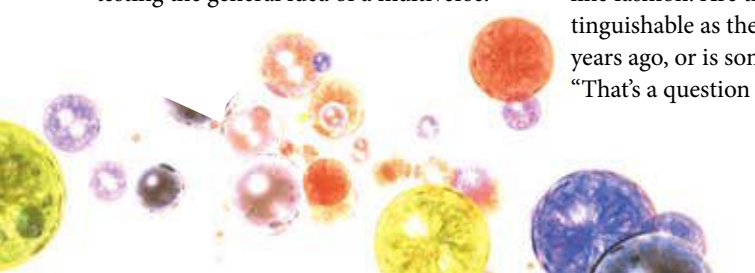
Worlds of worlds

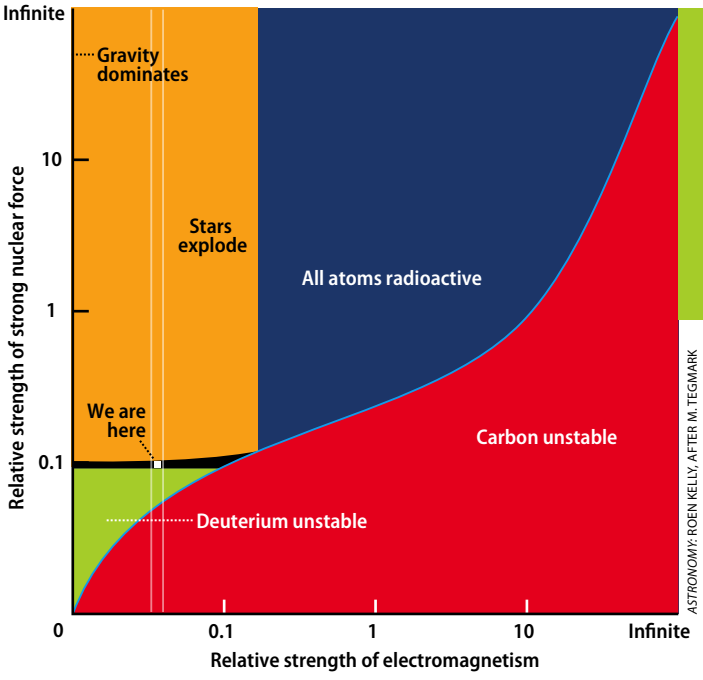
Let's suppose the eternal inflation theorists — Vilenkin, Linde, and Guth — are right, and universes are churned out in assembly-line fashion. Are these universes as indistinguishable as the Model Ts produced 80 years ago, or is some variation allowed? "That's a question for fundamental physics to address," says Vilenkin, who suggests the answer may come from a new idea called the "landscape of string theory."

The landscape — a term coined by Stanford physicist Leonard Susskind — stems largely from the fact that string theory requires 9 or 10 dimensions of space and one of time. The world we inhabit has three dimensions of space and one of time, which means the additional six or seven spatial dimensions need to be hidden — rolled up into toruses (donuts), for example, or wrapped into more complex shapes.

This bundling can be done in an estimated 10^{500} ways, each of which represents a stable configuration of space-time called a vacuum. Although string theory has one overarching set of laws, the specific rules governing each vacuum — as well as the vacuum energy, number of dimensions, types of particles and forces — depend on the geometry of the extra dimensions.

The scenario, in effect, allows for a huge number of conceivable worlds or





ASTRONOMY: ROEN KELLY, AFTER M. TEGMARK

PHYSICAL CONSTANTS took on values given by chance processes when the universe was born. But if they were any different, we couldn't exist.

universes, which can be pictured as random valleys, situated at slightly different elevations and spread across an immense landscape of possibilities.

The multiple universes that arise in string theory have nothing to do with inflation, yet the two ideas are complementary. "Eternal inflation shows you how to spin off multiple universes," explains Joseph Polchinski of the University of California, Santa Barbara. "The landscape shows you how those universes can have different physics."

Although it sounds like a happy union, not everyone is cheering. Inflation pioneer Paul Steinhardt of Princeton considers the landscape concept a step backward for physics. "We had hoped string theory would tell us how inflation really works," he says. "Instead, we're told the universe is much more complicated on large scales than we ever imagined, with inflation occurring in a large number of ways that vary from region to region."

"There's nothing surprising about theories that have lots of solutions," counters Susskind. "Any time you have many variables, you can expect a large number of solutions." Just as we accept biological theories that allow for millions of different species, we might have to accept physics theories that allow for many different vacuum states.

Physicists had hoped that string theory would explain our world with one solution, not a multitude. Polchinski, among others, shared that view, but now tries to keep an open mind. "Our job is to figure out the way nature is," he says, "not to tell it how to behave."

At this stage, it would be premature to consider the landscape a reality. Our understanding of string theory is still "tentative," Polchinski admits. "Every 5 to 10 years, we learn something that surprises us, which shows we don't have the full picture. Yet the evidence for the landscape is piling up, and it's time to start taking the idea seriously."

Dark energy

One of the strongest arguments in favor of string theory's landscape relates to the energy of empty space — the vacuum energy, or "dark energy." The standard explanation for this energy is that it maintains a single, unwavering value throughout space — thus becoming what Einstein called the cosmological constant.

The problem is that physicists don't know how to calculate the cosmological constant from first principles, the hallmark of a robust theory. The simplest calculations yield a value 10^{120} times bigger than measured values — "by far the all-time worst discrepancy between theory and experiment," notes Susskind.

The answer may come from combining the string-theory landscape, which shows how the cosmological constant can vary, with the "anthropic principle." The latter suggests the cosmological constant may be a variable like the weather — something that changes from place to place in the universe, rather than a true constant of nature.

If a broad range of values for the constant is possible, it's not surprising we live in a universe with a small cosmological constant, one where stars and planets can exist. In the same way, it's not surprising we live on Earth, rather than on Venus or Pluto, where we'd either roast or freeze.

HOW TO SPEAK COSMOLOGY

ANTHROPIC PRINCIPLE
We see the universe the way it is because if it were different, we would not be here to observe it.

COSMOLOGICAL CONSTANT
Originally, this was a mathematical term used by Albert Einstein to give space-time an innate tendency to expand. More recently, it refers to the accelerated cosmic expansion produced by dark energy.

DARK ENERGY
A residual energy in space that is causing cosmic expansion to accelerate; sometimes called vacuum energy.

FLATNESS
A flat universe is one whose space-time sits on the border between eternal expansion and eventual recollapse.

INFLATION
During an early period of extremely rapid growth, the observable universe expanded by a factor of 10^{30} or more in 10^{-33} second.

O-REGION
This is the observable universe, which may be only a fraction of the full universe.

SCALE INVARIANCE
The spectrum of the cosmic microwave background radiation appears nearly identical at all scales.

STRING THEORY
A theory in which the fundamental entities are not particles but tiny string-like loops of energy. Differing loop oscillations correspond to different elementary particles. Strings have length but no other dimension.

"Our job is to figure out the way nature is, not to tell it how to behave." — *Joseph Polchinski*

A large positive value for the cosmological constant would produce tremendous cosmic acceleration, and galaxies would never form. A large negative value, conversely, would cause the universe to collapse instantly, and no one would be around to ponder the cosmological constant problem.

Maybe there is a "magical explanation" for the cosmological constant — a mechanism yet to be discovered, says Harvard's Arkani-Hamed. The alternative is an environmental argument, which requires the existence of many different environments. Fortunately, the landscape provides "zillions" of them, he adds. "Given that the anthropic solution is the only thing that works at the moment, it makes sense to see where this idea leads."

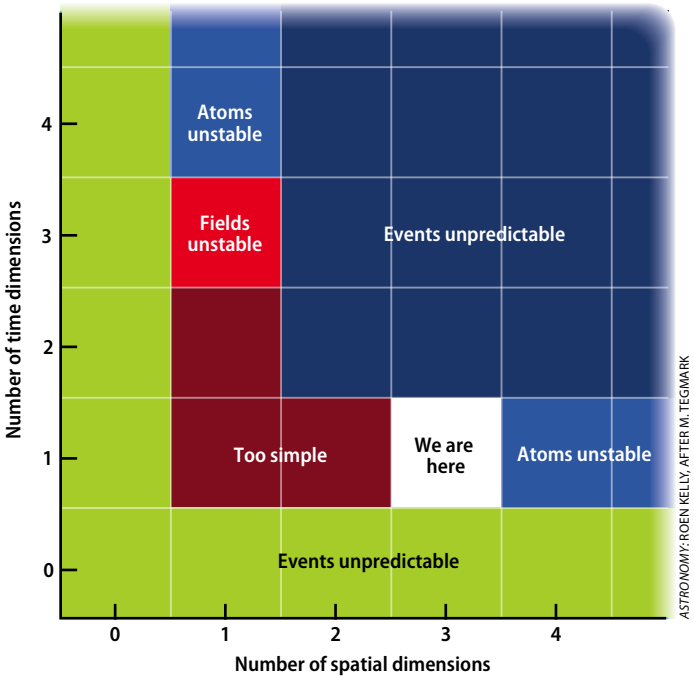
To a certain extent, it leads to trouble. The anthropic principle is widely disliked and elicits strong reactions. David Gross, a physicist at the University of California, Santa Barbara, hates the idea, calling it a "virus" that's hard to get rid of. Few scientists champion the anthropic principle, although many are resigned to the fact we might be stuck with it.

Last-resort universes?

Tegmark objects to the common practice of considering anthropic arguments "a last resort, which makes it seem like we have a choice." Any theory, he says, has to address selection effects, including biases stemming from the fact that any universe we observe must be habitable — "and that's the case whether you call it 'anthropic' or not."

John Peacock of the University of Edinburgh agrees, saying the anthropic principle is "not a retreat from physics but an advance." Once cosmologists seriously consider the possibility that the vacuum energy can differ from place to place — and that other parameters considered constant may vary as well — they will then need to work out the mechanism responsible for that variation. This can point us toward new physics. In the process, says Peacock, we may learn things about the universe.

SPACE AND TIME might have other values in other universes, but their fates would be quite different.



ASTRONOMY: ROEN KELLY, AFTER M. TEGMARK

But even if the anthropic principle is true, does it really explain anything? And can it help us make actual predictions?

In a 1987 paper, Steven Weinberg of the University of Texas employed anthropic-type reasoning to predict a small, non-zero value for the cosmological constant. If the cosmological constant can assume a range of values, he reasoned, probably it will not adjust itself exactly to zero. "The value we now measure for the cosmological constant is precisely what Weinberg predicted," notes Polchinski. "It would be great if that's not a one-time thing and there are other things we can predict."

It will be hard to use the anthropic principle to determine which worlds, or universes, are most probable, says Linde. The difficulty lies in measuring probabilities for infinitely-large sets. "There are many different ways of counting infinities, and we don't know which methods are preferable."

Susskind agrees it will be a long time before we can use the anthropic principle in a predictive way: "At the moment, it's telling us more about what not to do than what to do." For example, perhaps we shouldn't keep trying to explain why the cosmological constant is what it is, he says, "when the only explanation may be that in a universe with a large number of possibilities, we live in an environment that supports life."

Many versions of the anthropic principle are guaranteed to be true and, therefore, do not meet the standards of science, Vilenkin points out. Before anthropic arguments can carry us further, he says, we'll need statistical techniques that support testable predictions.

But even if that effort succeeds, there are limits to how far we can go, he notes. "It looks like all we can hope to predict is the probability distribution, saying, for instance, with 90-percent confidence what the mid-range value of the cosmological constant is likely to be." Sharpening the prediction further may be impossible.

While some may find that disappointing, Vilenkin says, "Were it not for the multiverse picture and anthropic arguments, we'd have no tools for thinking about the structure of the universe beyond our horizon."

But now there's a tantalizing, new possibility, he adds: "By doing measurements in our own region, we can test our predictions for what lies beyond."

The return of cosmic

Infinitely long, exceedingly thin, and unimaginably dense strands of primordial matter may wind their way through the universe. /// BY STEVE NADIS

Cosmic strings have led a checkered past: popular in the 1980s, denounced in the 1990s. Now, theoretical revisions support the idea that ultradense strands of matter could be the "seeds" for galaxy formation.

Even Edward Witten of the Institute for Advanced Study, widely recognized as one of the world's greatest theoretical physicists, now believes "strings of different sizes and kinds probably exist" — despite the fact that, 20 years ago, Witten argued convincingly none was to be found. So, why are scientists now getting wound up about cosmic strings?

Much of the impetus comes from revisions to string theory, which describes fundamental forces and particles as tiny, string-like loops of energy. Current versions of the theory show strings — the basic units of energy and matter — can reach astronomical sizes.

These strings, argues Joseph Polchinski from the University of California, Santa Barbara, would have been produced after inflation, which otherwise would dilute them to oblivion. Reformulated cosmic strings are stable over the age of the universe and less massive than the strings Witten and others contemplated in the 1980s. This means their influence on the universe would be less dramatic than previously thought, so they can't be ruled out by recent observations.

Defects in space

Witten concedes Polchinski and his colleagues deftly address the difficulties he raised, yet one question remains: Can we detect cosmic strings?

Maybe. Two research teams report evidence for cosmic strings in different parts of the sky. While these claims have yet to be either verified or refuted, they have "breathed new life into this field," says Alexander Vilenkin of Tufts University, who in the 1980s first suggested cosmic strings could trigger galaxy formation.

Cosmic strings are second only to black holes in the astrophysicist's zoo of weird objects. They are narrow, ultradense filaments formed during a phase transition — called inflation — within the first microsecond of cosmic history. Just as cracks can appear in ice as water changes from liquid to solid, the universe could have developed topological defects as it inflated. Linear defects would have formed at junctures where different areas undergoing the transition ran into each other, leaving behind slender threads of unconverted material forever trapped in a primordial state.

Cosmic strings, the theory says, emerged from this phase transition in a spaghetti-like tangle. Individual threads move at significant fractions of the speed of light.

strings

ONCE CONSIGNED to cosmology's trash bin, cosmic strings have returned with a vengeance. Because a cosmic string acts like a cylindrical gravitational lens, astronomers may be able to trace a string's location by looking for pairs of identical galaxies. In one intriguing case, some researchers think they've found one. LYNETTE COOK FOR *ASTRONOMY*

WHEN STRINGS COLLIDE, they can exchange pieces and form a free-floating loop. In this computer simulation, two strings approach one another at half the speed of light, emitting radiation — usually gravitational waves. A new loop forms in the collision's aftermath.
R. BATTYE AND E. P. SHELLARD, UNIVERSITY OF CAMBRIDGE

They're either long and curvy, with a complex assortment of wiggles, or fragmented into smaller loops that resemble taut rubber bands.

Although thinner than subatomic particles, cosmic strings are boundless in length, stretched by cosmic expansion across the universe. They are physically characterized by their mass per unit length, or tension, a parameter that reflects their gravitational heft. This linear density can reach incredibly high values — about 1 million metric megatons per centimeter for strings formed at the so-called grand unification energies (10^{16} billion electron volts and higher), corresponding to a time when all four fundamental forces in nature were combined as one.

Steve Nadis *is a science writer and frequent* Astronomy *contributor who lives in Cambridge, Massachusetts.*

"Neutron stars are among the densest compact objects we know of, but even if we squeezed one billion neutron stars into the size of an electron, we would still hardly reach the matter-energy density characteristic of grand unified cosmic strings," notes Alejandro Gangui, an astronomer at the University of Buenos Aires.

String lenses?

Objects this massive must have a phenomenal gravitational influence. If a string ran between the Milky Way and another galaxy, light from that galaxy would go around the string symmetrically, producing two identical images near each other in the sky.

"Normally you'd expect three images, if lensing is due to a galaxy," says Vilenkin, with some light traveling straight through the lensing galaxy and other rays traveling around either side. Light can't go through a string because the string's diameter is much smaller than the light's wavelength, so strings produce only two images.

A Russian-Italian group led by Mikhail Sazhin of Moscow State University has recently discovered remarkably similar double images of a galaxy named CSL-1 in the constellation Corvus. Both images have the same redshift (0.46), and their spectra are "identical at a 99.96-percent confidence level," claims Giuseppe Longo, a collaborator from Federico II University in Naples. The data "can be interpreted either as the chance alignment of two identical galaxies," the Italian team says, "or as the first case of lensing by a cosmic string."

Vilenkin considers this observation an "intriguing case that a string could explain quite naturally." Thomas Kibble of Imperial College in London, whose 1976 paper sparked interest in cosmic strings, thinks there's a reasonable chance a cosmic string is responsible for the images. "I won't bet heavily on it, but I might make a small wager," he says.

There's nothing uncommon about finding pairs of galaxies in the sky, counters Harvard University cosmologist Abraham Loeb: "Andromeda and the Milky Way are close together, and, to a distant observer, they might look very similar."

There's no way to exclude the possibility of two similar galaxies sitting next to each other by coincidence, agrees Case Western Reserve physicist Tanmay Vachaspati. If there is a cosmic string there, he says, the number of double images in its vicinity should exceed that expected by chance. Sure enough, Sazhin and colleagues found 11 other pairs in the area around CSL-1. Their next step is to obtain more detailed spectroscopy with the European Southern Observatory's Very Large Telescope in Chile to find out how similar these paired galaxies really are.

The team also is pursuing another, possibly more definitive, test: trying to determine whether the images are truly identical or just vaguely similar. Lensing by a galaxy leads to gone unnoticed seems unlikely — and the mass requirement only increases for more distant objects.

On the other hand, a cosmic string loop within our galaxy could produce the fast oscillations. A period of 80 days implies a loop about 160 light-days long. Trucking through our galaxy at a substantial fraction of light-speed, the loop might spend only a year in the line of sight between Earth and the Double Quasar. — *Francis Reddy*

THE DOUBLE QUASAR

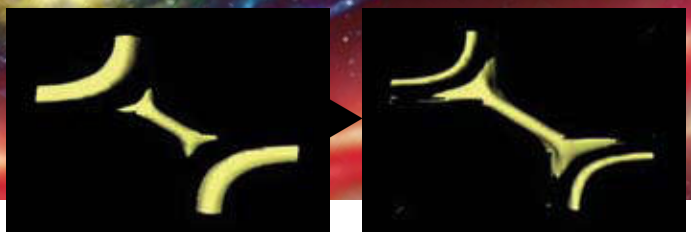
In 1979, radio astronomers found the Double Quasar, Q0957+561A/B, in Ursa Major. A foreground galaxy cluster creates two identical images of the same quasar separated by 5.7". This was the first confirmed gravitational lens, and it has played a pivotal role in astronomers' understanding of the phenomenon.

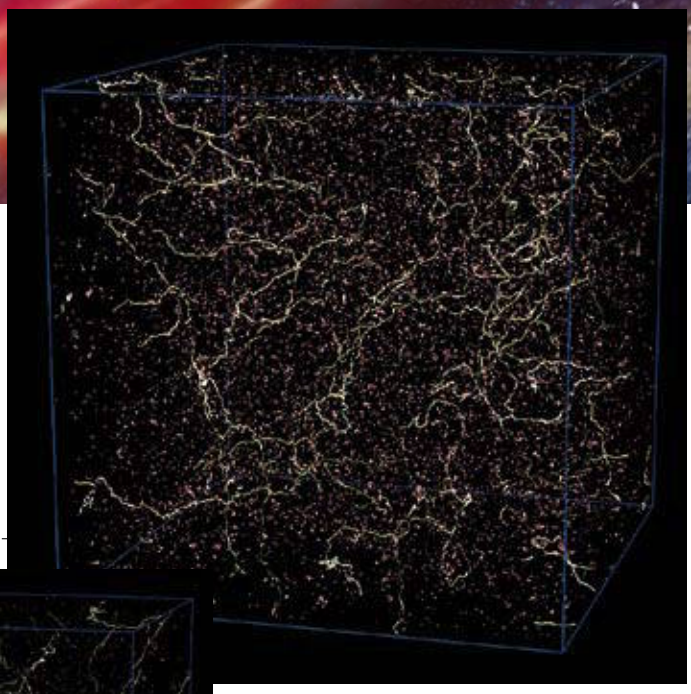
In August 2004, a team led by Rudolph Schild of the Harvard-Smithsonian Center for Astrophysics detected concurrent brightness changes in both quasar images. Looking at data from 1994 and 1995, the astronomers found several oscillations with a period of about 80 days. If these changes have a common origin, the astronomers reasoned, they must be due to a large object very close to us.

Schild and colleagues calculated a binary pair of 78-solar-mass stars within 4 light-years of Earth could cause the effect. But the idea that such stars would have

NOAO/AURA/NSF

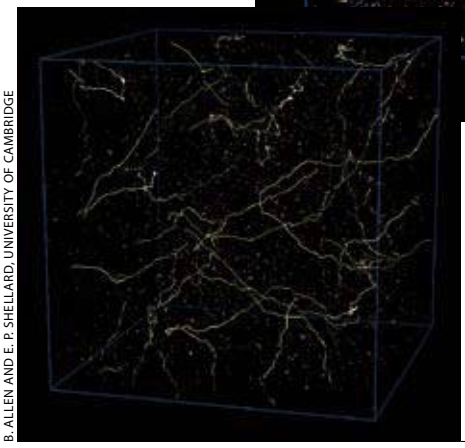
A MASSIVE GALAXY splits the distant quasar's light and forms two images.





B. ALLEN AND E. P. SHELLARD, UNIVERSITY OF CAMBRIDGE

▶ WHEN COSMOLOGISTS MODEL cosmic-string evolution, their main goal is to predict how a number of averaged properties — such as the speed, separation, and number of strings in a given volume — change over time. The simulation at right shows strings when the universe was young and dominated by radiation, in its first 10,000 years. Space is filled with cosmic strings. Long strings have many "wiggles," and there's a high density of small string loops.



B. ALLEN AND E. P. SHELLARD, UNIVERSITY OF CAMBRIDGE

◀ A SNAPSHOT OF A STRING NETWORK in the universe's matter-dominated era — after the first 10,000 years — shows a much-lower density of both long strings and loops. Also, long strings display fewer wiggles. Simulations of string evolution help cosmologists test how effectively cosmic strings can trigger galaxy formation.

distorted images that differ in size and shape — light passing far from the galaxy appears to bend less than light passing nearby. A cosmic string bends light by the same amount no matter how far light passes from it. So, if the string is straight, it will produce two undistorted images with a sharp edge between them — like a pair of snapshots sitting side by side. "No other phenomenon to our knowledge can produce such a morphology," says Longo. If the astronomers see a sharp edge with the Hubble Space Telescope, the only instrument with sufficient angular resolution, they'll be confident it is a string.

Meanwhile, there may be another cosmic string floating around our galactic neighborhood. The idea — postulated by Rudolph Schild of the Harvard-Smithsonian Center for Astrophysics and three colleagues from Kiev Observatory — is that brightness oscillations in a well-known quasar, Q0957+561A/B, are explained most plausibly by a cosmic string loop located within our galaxy's halo.

A BILLION NEUTRON STARS crushed to an electron's size wouldn't match cosmic-string densities.

Monitored since 1979, Q0957 is the first-known example of gravitational lensing. A distant galaxy serves as the lens, which creates two images of the quasar that show the same brightness oscillations, although separated by a 1.1-year time delay. But during a 400-day period in 1994 and 1995, the brightness of the two images oscillated in synch, with no time lag. Schild and company attribute this anomaly to a gravitational lens. They think a rotating string loop flew across our line of sight in 1994 and 1995, simultaneously affecting both quasar images. More conventional explanations, such as lensing by a double-star system, already have been ruled out.

Fermilab physicist Mark Jackson finds the explanation interesting, but inconclusive. "We need a more sophisticated [cosmic string] model to see if it holds together," he says.

Finding a nearby cosmic string — estimated at 10,000 light-years away — is highly unlikely, although not impossible, says Vachaspati. Computer simulations suggest long strings should be spaced roughly 325 million light-years apart. But for now, he doesn't have a better explanation for the synchronous blinking.

What's needed, says Tufts physicist Ken Olum, is a statistical analysis that would reveal whether the unexpected brightness fluctuations are, in fact, real. Schild concurs and is working on that problem with Bell Labs mathematician Dave Thomson.

Confirmation of just one lensing event by a cosmic string would be momentous. Researchers can estimate the string's tension by determining the extent to which light is bent. The tension, in turn, reflects the energy scale of the primordial phase transition that gave rise to the string. Knowing this energy scale would help cosmologists limit possible models of the early universe.

With one lensed pair in hand, investigators will try to trace out the string's path in the sky. "The string will cut through the middle of the two objects, but the angle is hard to determine," explains Vachaspati. Most likely, the search will be hit-or-miss at first, as astronomers scour the surrounding area. But as more pairs are found, the path of the string should become clearer. "You can search in optical, infrared, radio, whatever you like," says University of California, Berkeley, astrophysicist George Smoot. "A cosmic string would treat all light alike."

STRING SPEAK

COSMIC STRING
A hypothesized defect in space-time created when the universe cooled.

GRAVITATIONAL LENS
A massive object, such as a group of galaxies, that warps space and alters the path of radiation passing near it.

GRAVITATIONAL WAVE
A propagating gravitational field produced by some change in the distribution of matter. Predicted by Einstein, gravitational waves travel at the speed of light, exerting forces on masses in their paths.

SPACE-TIME
A combination of all spatial dimensions and time.

QUASAR
The brilliant core of a distant galaxy, thought to be powered by a supermassive black hole.

Once there's an unambiguous case of lensing by a string, Polchinski adds, "We'll want to do a systematic search." He predicts the science will move quickly after astronomers verify the first discovery. "We're likely to go from one event to 1,000 events in 10 years." While this survey proceeds, people will continue to invent new ways of looking for strings.

The cosmic microwave background (CMB), for example, offers another avenue. Cornell University physicist Henry Tye suggests cosmic strings may be responsible for 10 percent of the temperature differences (and related density fluctuations) in the CMB, thereby contributing to the creation of galaxies and galaxy clusters. Smoot says he and other researchers are waiting for better data to pin down what, if any, role strings played in structure formation.

Even if a supporting role is ultimately ruled out, cosmic strings should still create a linear discontinuity in the CMB — two regions with slightly different temperatures. This temperature difference stems from the Doppler effect: Photons on one side of the fast-moving string get pushed, which gives them a higher frequency and temperature than photons on the other side that are not pushed. Although this effect has not yet been documented in CMB data, it may be detectable, says Tye, depending on how fast the string is moving and its tension or mass.

Looking with LIGO and LISA

Long threads of superdense material moving near the speed of light should throw off lots of gravitational radiation — an effect predicted by Albert Einstein almost 90 years ago. The Laser Interferometer Gravitational-wave Observatories (LIGO) in Louisiana and Washington might be able to detect such a disturbance. Vilenkin, who first considered gravitational radiation from strings in 1982, says, "This may be the only source of gravitational waves LIGO could detect."

The most visible signal would be produced by a cusp — a transient spike that forms when wiggles traveling along a cosmic string in opposite directions momentarily meet. As the cusp straightens itself out, its tip moves at the speed of light. "Like the crack of a whip, a great deal of energy is concentrated in the tip," Polchinski notes, "so it emits an intense beam of gravitational waves in the direction of its motion."

Cusps are the easiest thing LIGO could spot, says LIGO team member Xavier Siemens of the University of Wisconsin, Milwaukee. Such a signal is within reach of the current LIGO, says Siemens, and it should be even more prominent when the "advanced" version comes online in a few years. With its greater sensitivity, the Laser

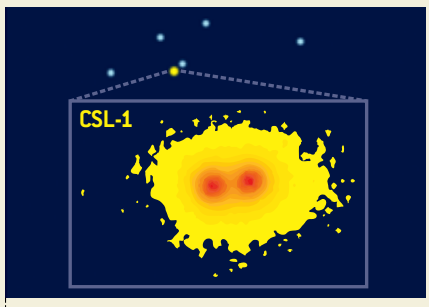
CAPODIMONTE STERNBERG LENS CANDIDATE 1 (CSL-1)

Images produced by garden-variety gravitational lenses — foreground galaxies or galaxy clusters — typically come in odd numbers and differ significantly in brightness. Cosmic strings should act as cylindrical gravitational lenses, creating nearly identical double images of any sources behind the strings.

In 2003, collaboration between Capodimonte Observatory in Naples, Italy, and Sternberg Astronomical Institute at Moscow State University turned up a close pair of seemingly similar elliptical galaxies in Corvus. Now known as Capodimonte Sternberg Lens candidate 1 (CSL-1), the galaxies appear to be twins separated by 2". If the pairing is a coincidence, it's a remarkable one, and there's no sign of a giant foreground galaxy that might serve as a traditional lens. A team led by Moscow State's Mikhail Sazhin concluded the best explanation was lensing by a cosmic string.

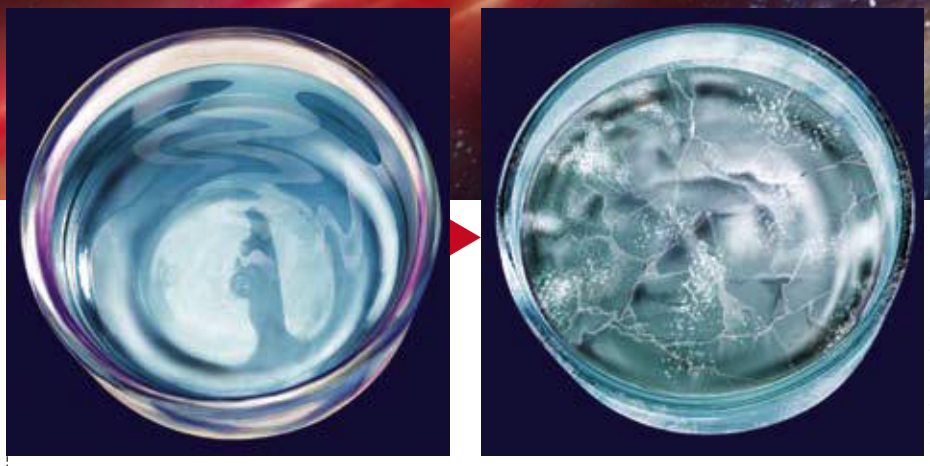
The same team then searched for pairs among the roughly 2,200 galaxies near CSL-1. The astronomers found 11 pairs that, on the basis of separation and color similarity, could be lensed galaxies. Conventional lensing, they argued, should produce no more than two pairs in the same field of view, while a cosmic string could produce as many as 200, depending on its precise configuration.

A cosmic string should leave its distorting imprint on the CMB. Using Wilkinson Microwave Anisotropy Probe data, astronomers Amy Lo and Ned Wright of the University of California, Los Angeles, searched for and found an edge in the microwave background at CSL-1. But if the edge is real, a cosmic string responsible for it must be moving at more than 96 percent of light-speed — unlikely, they conclude. Critical tests of CSL-1 must await detailed data from facilities now being built, such as the European Space Agency's Planck probe. — *F. R.*



ASTRONOMY: JAY SMITH

CSL-1 (inset) and other paired galaxies (light blue) may trace a cosmic string.



ASTRONOMY: JAY SMITH

COSMIC STRINGS FORMED as defects in space-time when the universe cooled. The process is analogous to cracks that form as water freezes to ice.

Interferometer Space Antenna (LISA), due to be launched next decade, would have a better chance of intercepting a cusp signal.

Because a cosmic string is a piece of the universe from a more energetic state, it provides a unique view of the physics that prevailed when it was created. "Cosmic strings might actually provide the best observational window into fundamental string theory," notes Imperial College's Thomas Kibble, while also offering the chance to test the predictions of string-based inflation models.

Most of those models are now based on "brane inflation," an idea advanced by Tye and New York University physicist Gia Dvali in 1999. Inflation, they suggest, ensued when two stacks of three-dimensional membranes, or branes, drifted toward each other in higher dimensions due to gravity's tug. In this scenario, inflation ended when the branes collided and melted, creating the Big Bang.

Polchinski likes the Dvali-Tye scenario because it shows where the energy that drives inflation comes from. "Brane inflation offers a natural geometric picture that automatically leads to the right phase transition that produces cosmic strings," he says.

Two kinds of cosmic strings were created during that phase transition, according to Tye: F-strings, the basic building blocks of string theory that make up electrons and protons, stretched across the entire sky; and D-branes, which assume various forms, including one-dimensional strings. "Brane inflation gives you all you need for cosmic strings to survive and be observable," says Dvali. What's more, adds Tye, string tensions predicted by brane inflation are compatible with the latest observations.

How would these cosmic strings differ from the "old-fashioned" ones discussed by Kibble and Vilenkin in the 1970s and 1980s, before string theory took off? To simplify the terminology, some researchers use the term *cosmic superstrings* to distinguish new string-theory versions from the cosmic strings of old. "Every idea that existed for conventional cosmic strings has a counterpart in string theory," says Fermilab's Mark Jackson. But the concept is much richer because it predicts a greater variety of superstrings.

Superstrings travel in different dimensions and have a range of tensions, whereas scientists expect traditional cosmic strings have uniform tensions. In string theory, three different cosmic superstrings can join to form a junction, and each would have a different tension that fits a specific relationship, says Jackson. The old kind of cosmic strings don't form junctions.

COSMIC STRINGS OFFER a glimpse of physics at energies far greater than accelerators can reach.

What happens when strings collide also differentiates them. Cosmic strings almost invariably reconnect, meaning the two strings intersect to form an X. The X, in turn, breaks off to form two Vs. The Vs become vibrating loops that decay through gravitational radiation and eventually disappear. Cosmic superstrings, by contrast, don't always reconnect; they can pass through each other without crossing because they move in higher dimensions.

The difference should have significant observational consequences. There should be more long cosmic superstrings around than cosmic strings simply because superstrings cut themselves up less often. "By looking at the sky and counting the number of long strings, we may be able to tell whether they are ordinary cosmic strings or superstrings," says Vilenkin.

A cosmic-string "census" would be helpful in this regard, but for the time being, such an effort will have to be accomplished with a computer rather than a telescope. Simulating the distribution of cosmic strings is exceedingly difficult, says Polchinski, in part because of the dynamic range: from loops on the light-year scale to long strings extending 10 billion light-years or more. Plus, the system itself is intrinsically complex to model, with long strings and smaller loops moving, crossing, and oscillating in nonlinear ways — all occuring in an expanding universe. Although detailed computer simulations could help scientists predict how strings are arranged in the sky, it may take a credible detection before researchers take on such a project.

Vilenkin, along with Tufts colleagues Ken Olum and Vitaly Vanchurin, is developing a simulation to determine the curviness of strings and the number and size of their wiggles and loops — all of which affect the gravitational waves likely to be produced. A major undertaking, it could provide insights on cosmic-string evolution, which remains poorly understood.

Knowledge gained from simulations, theory, and observations offers a large potential payoff. "This will be a window on physics at energies up to a trillion times higher than particle accelerators can reach," Polchinski says. "We're really at the dawn of a new era of science."

And cosmic strings, which not long ago seemed destined for the rubbish bin of physics, are now center stage. Well, maybe not exactly at the center: They may be lurking, instead, at our galaxy's edge.

The great neutrino hunt

Ghostly neutrinos offer clues about everything from our Sun to the early universe. The trick is capturing them. /// BY ALISON BOYLE AND KEN GRIMES

Elusive, intangible, mysterious. For three-quarters of a century, neutrinos have proven the most ghostly of all the quantum entities that make up the universe. As physicist Ray Davis, Jr., explains, "A neutrino passing through Earth has only one chance in a thousand billion of being captured." Yet, for all of neutrinos' difficulty of detection and bizarre behavior, new theoretical work suggests understanding them will help lead physics to a Theory of Everything.

Meanwhile, neutrinos have haunted not only individual physicists and astronomers, but humans' best attempt to sketch the deep workings of the cosmos: the standard model of particle physics. Dedicated scientist teams — cosmic ghostbusters — have pursued this insubstantial presence, rewarded only by intermittent glimpses of its strange lineaments. Yet, on several occasions, most recently in 2002 for Davis and fellow physicist Masatoshi Koshiba, this dogged pursuit has earned these researchers the physics world's most glittering prize: the Nobel.

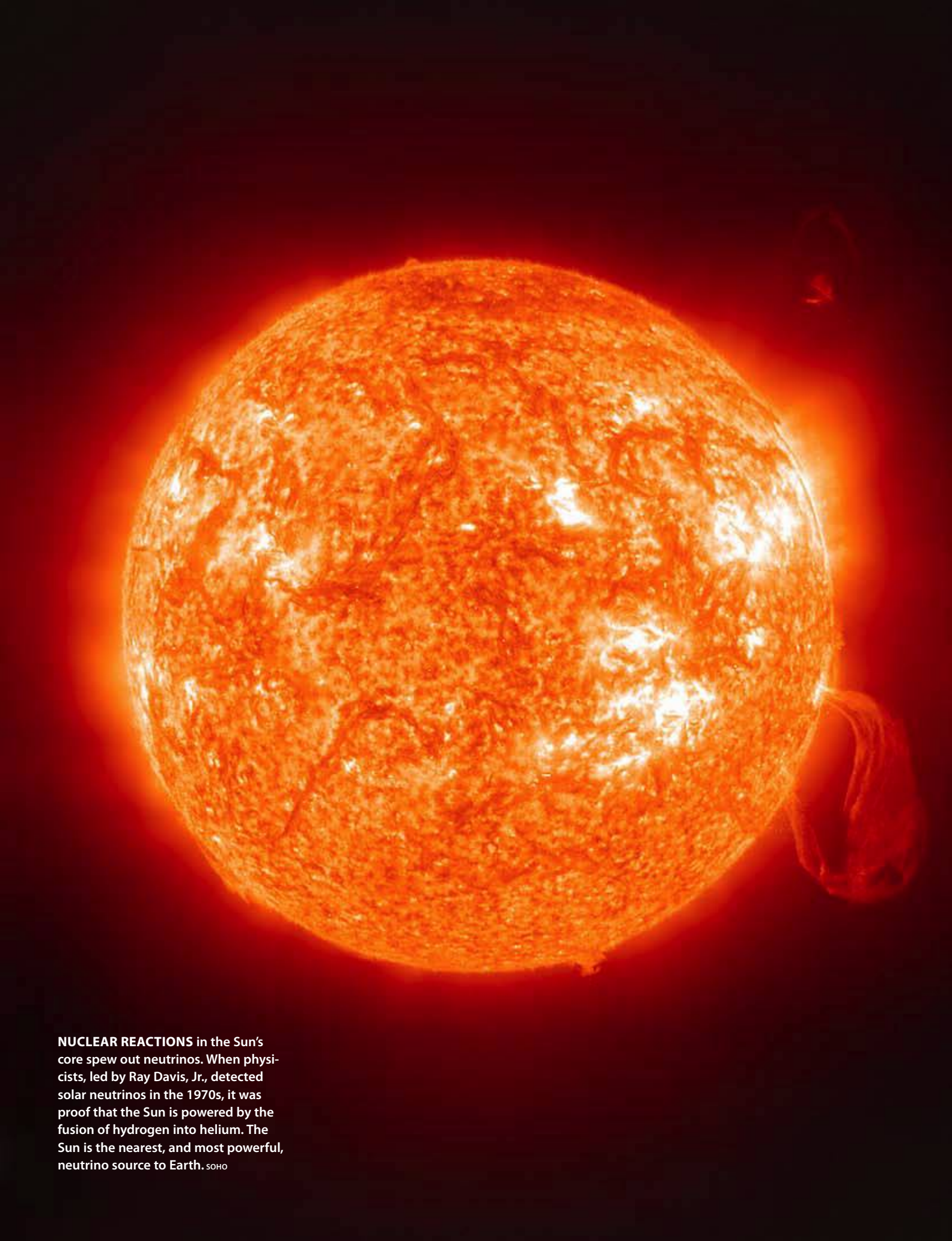
The original neutrino-ghost "seer" was physicist Wolfgang Pauli. His vision was mathematical. In the late 1920s and 1930s, the early years of quantum physics, Pauli pondered the problem of beta decay. A radioactive process in the atomic nucleus, beta decay emits an electron as a neutron transforms into a proton. According to the best measurements, something was missing. The sum of the particles' momenta before the decay seemed greater than afterward. Such a mismatch violates one of the bedrocks of physics: the principle of energy conservation.

In 1930, while baffled physicists tinkered with theoretical and experimental details, Pauli proposed a more radical — or as he termed it, desperate — remedy. At a time when the known particles numbered just a handful, Pauli proposed an entirely new, unseen, massless, and chargeless particle to carry off the missing energy without a trace. Pauli ruefully apologized to future hunters: "I have done a terrible thing. I have postulated a particle that cannot be detected." A few years later, Italian physicist Enrico Fermi took up the task. In 1934, Fermi produced a comprehensive theory of beta decay that described how a weak nuclear force could make atomic nuclei unstable, producing transformations in subatomic particles. The theory depended on Pauli's hypothetical entity, to which Fermi now gave the name *neutrino* (Italian for "little neutral one"). Despite continued skepticism, Fermi's theory gradually gained acceptance because it accurately explained many experimental results.

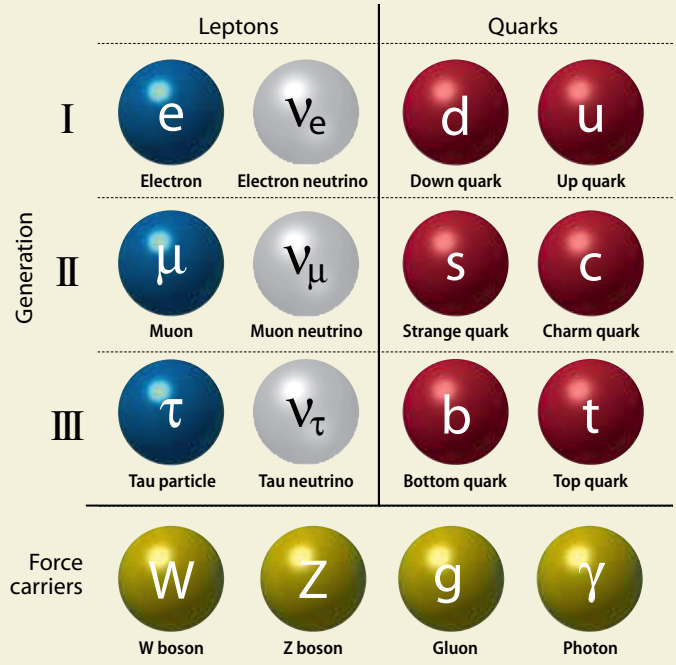
Meanwhile, other physicists were trying to solve what seemed like a different mystery — what makes the Sun shine. In the late

NEUTRINOS can pass through normal matter *several light-years* thick. No wonder they've earned the name "ghost."

Alison Boyle *and* **Ken Grimes** *are London-based science writers.*



NUCLEAR REACTIONS in the Sun's core spew out neutrinos. When physicists, led by Ray Davis, Jr., detected solar neutrinos in the 1970s, it was proof that the Sun is powered by the fusion of hydrogen into helium. The Sun is the nearest, and most powerful, neutrino source to Earth. SOHO



ASTRONOMY: ROEN KELLY

THE STANDARD MODEL OF PARTICLE PHYSICS

According to physics, the world is made from 12 fundamental particles called fermions: six quarks and six leptons. All the hundreds of known particles are combinations of these. In our everyday life, we see only what's termed Generation I fermions. These are electrons and the up and down quarks (which combine to form neutrons and protons).

Fermions in Generations II and III tend to decay into lower generations, and when a heavy lepton (an electron, a muon, or a tau) decays, one of the by-products is a correspondingly named neutrino.

Matter particles interact by exchanging force particles, collectively called bosons, shown at the bottom of the diagram. At present, the standard model can explain how force particles carry the strong, electromagnetic, and weak forces, but it can't explain gravity.

All particles have a particular mass, electric charge, and spin. Each particle also has a corresponding antimatter particle with the same mass and spin but a different electric charge. When a particle meets its antiparticle, the two annihilate in a flash of energy.

A particle changes its spin, or handedness, by interacting with another particle (yet undetected) called the Higgs boson. In the standard model, neutrinos and antineutrinos come only in left-handed varieties, so they're massless. But now it appears neutrinos have mass, so right-handed neutrinos must exist. Somewhere. — *Robert Burnham*

1930s, another Nobel winner, Hans Bethe, worked out the basic principles of how nuclear reactions power stars. It became apparent that neutrinos held the key to proving his theories. Why? Because like other ghosts wandering the Earth, neutrinos bear a tale of past trauma. As Davis puts it, "Neutrinos tell us what happened in the center of the Sun 8 minutes ago."

With Bethe's theory, neutrinos began their starring role in astronomy — and a problematic entanglement in the standard model of particle physics. The standard model is a theoretical description of the forces and basic building blocks of the universe. Fermi's theory was the first workable exposition of the weak force, one of the four fundamental interactions in the standard model. The others are the electromagnetic force, through which electrically charged particles like electrons and protons interact; the strong force, through which "color-charged" particles like quarks interact, for example to make up protons and neutrons; and finally, the gravitational force, by which any two bodies with mass attract each other.

This fourfold model helps explain the neutrino's eerie ability to walk through walls and worlds. Of the four fundamental interactions listed, neutrinos are considered immune to three. Lacking electric charge, neutrinos ignore electromagnetic interactions. Lacking color charge, they are indifferent to the strong interaction. Lacking mass, they are unaffected by the gravitational interaction. So what's left? Only the weak-force interactions that produce neutrinos through beta decay.

As their name suggests, weak interactions are rather feeble. They usually do not give neutrinos enough of a kick to produce reactions when they collide with other particles. As a result, neutrinos pass freely through materials built from atoms — paper, people, planets. In fact, neutrinos can pass unhindered through normal matter *several light-years thick*. No wonder they have earned the nickname "ghost."

"NEUTRINOS tell us what happened in the center of the Sun 8 minutes ago." — *Ray Davis, Jr.*

Tools of the trade

At first, no one attempted to prove the neutrino's existence. But in the early 1950s, experimental physicists Fred Reines and Clyde Cowan opened the next chapter in the ghost story — on a dare. Asked why they wanted to detect the neutrino, Reines replied, "Because everyone said you couldn't do it." Their experiment, called Project Poltergeist, combined high and low technologies in an original way. Nuclear reactors provided a reliable, artificial alternative to natural neutrino production, while state-of-the-art sensors detected particles as brief flashes of light inside a big water-filled tank placed deep within a mine. By 1955, Reines and Cowan announced the first experimental proof for the neutrino, a particle described by Reines as "the most tiny quantity of reality ever imagined by a human being."

Reines and Cowan's original tool kit became almost standard issue for succeeding neutrino-chasers. It's easy to see why. Neutrino detection presents huge experimental problems. The rarity of neutrino interactions demands a plentiful source of particles and a large absorption device, called a neutrino target. The tiny energy amounts involved require sensitive measuring devices well protected from Earth's background radiation.

In 1962, Nobel winners Leon Lederman, Melvin Schwartz, and Jack Steinberger built a 10-ton spark chamber, a target made from ninety 1-inch-thick aluminum plates, and a 43-foot-thick,

2,000-ton steel shield built of armor plating from scrapped ships. An artificial source delivered neutrinos in pulses of 10 million particles. The results: They identified a new species of neutrino — the muon. Whereas the original neutrino is associated with the electron (and is now called the electron neutrino), the muon neutrino derives its name from another subatomic particle, the muon.

Nobel winner Martin Perl predicted the third neutrino type (physicists refer to neutrino types as "flavors"), the tau, in 1978. However, the tau neutrino had to wait until 2000 before scientists confirmed its existence. These three neutrinos — electron, muon, and tau — coupled with their three like-named particles, constitute half of the 12 known fundamental building blocks (see "The standard model of particle physics" on the opposite page).

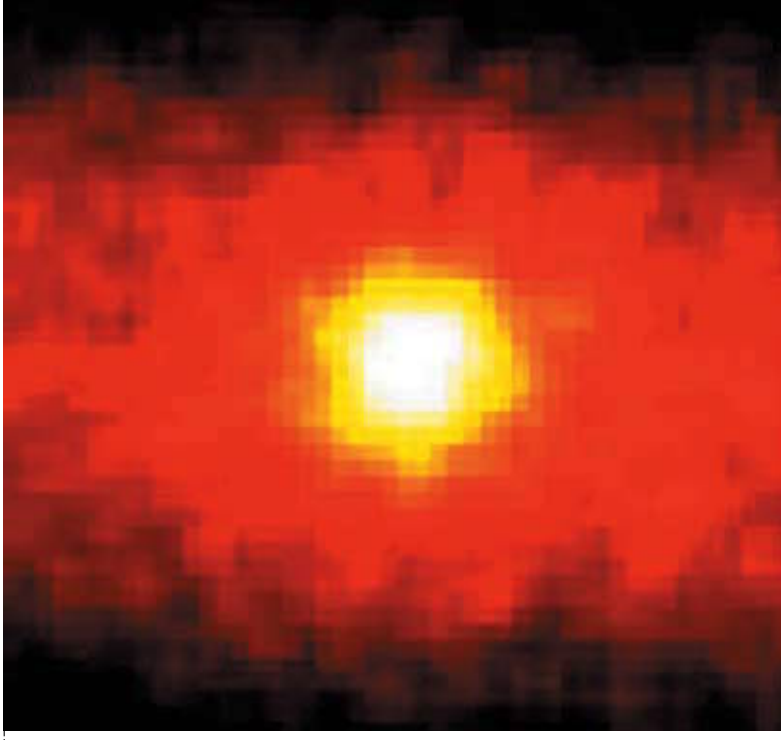
Solar ghosts

If detecting neutrinos was difficult when the detector sat next to a source spewing swarms of them, then what were the chances of identifying a natural neutrino originating 93 million miles away in the Sun? Yet, capturing a few of them would be the only way for scientists to confirm that the Sun runs on nuclear processes similar to those producing homegrown neutrinos in reactors.

Hans Bethe determined that for stars about the Sun's size, the major energy source is hydrogen converting into helium. In each cycle, four hydrogen nuclei fuse to form a helium nucleus. This is less massive than the initial constituents, and the leftover mass converts to radiation via Einstein's famous formula, $E=mc^2$. As with Pauli's original vision, the numbers must all add up, so other particles come into play to balance the equations. The net by-products of the hydrogen-helium reaction are two positively charged electrons (called positrons) and their comrades, two electron neutrinos.

In the 1940s, Bruno Pontecorvo and Luis Alvarez suggested a possible method for capturing natural neutrinos. According to their theory, an electron neutrino originating in the Sun should, if it collided with the nucleus of a chlorine atom, produce a radioactive atom of argon. All a would-be detector needed, then, was the experimental deftness to construct a chlorine-rich target massive enough to catch a natural neutrino. (The odds, however, are 10-quadrillion times smaller than those of capturing the natural neutrino's reactor-bred cousin.) The second part of the problem was equally tricky: isolating the resulting single argon atom. This has roughly the same likelihood as locating one particular grain of sand in the Sahara Desert.

No takers to the challenge appeared until the 1970s. Ray Davis, Jr., an experimental physicist with a background in chemistry, built a neutrino detector consisting of a tank holding 100,000 gallons of chlorine-rich dry-cleaning solution, equipped with batteries of single-atom argon detectors. To isolate the detectors from other radiation sources, Davis placed the tank 4,800 feet (1,460m) underground in a gold mine in Homestake, South Dakota. Davis faced not only astronomical odds, but also widespread skepticism at a time when, in his own words, "Not everyone would be willing to say that [they] believed in the existence of the neutrino."



A 500-DAY TIME-EXPOSURE of the Sun with the Super Kamiokande detector produced this image of neutrinos coming from nuclear reactions in the solar core. R. SVOBODA AND K. GORDAN/LSU

Despite such obstacles, Davis managed to extract an average of 17 argon atoms from 10^{30} chlorine atoms every month for a quarter-century, trapping a total of about 2,000 electron neutrinos.

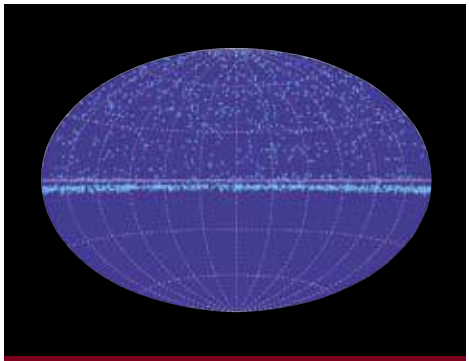
Davis' results confirmed that the Sun, in fact, does produce neutrinos and, therefore, is powered by the thermonuclear fusion of hydrogen into helium. More than this, though, the Nobel citation recognized Davis' visionary role in doing the undoable and establishing a new branch of astrophysics: solar-neutrino research. However, his results also produced a new conundrum.

Phantom shapeshifters

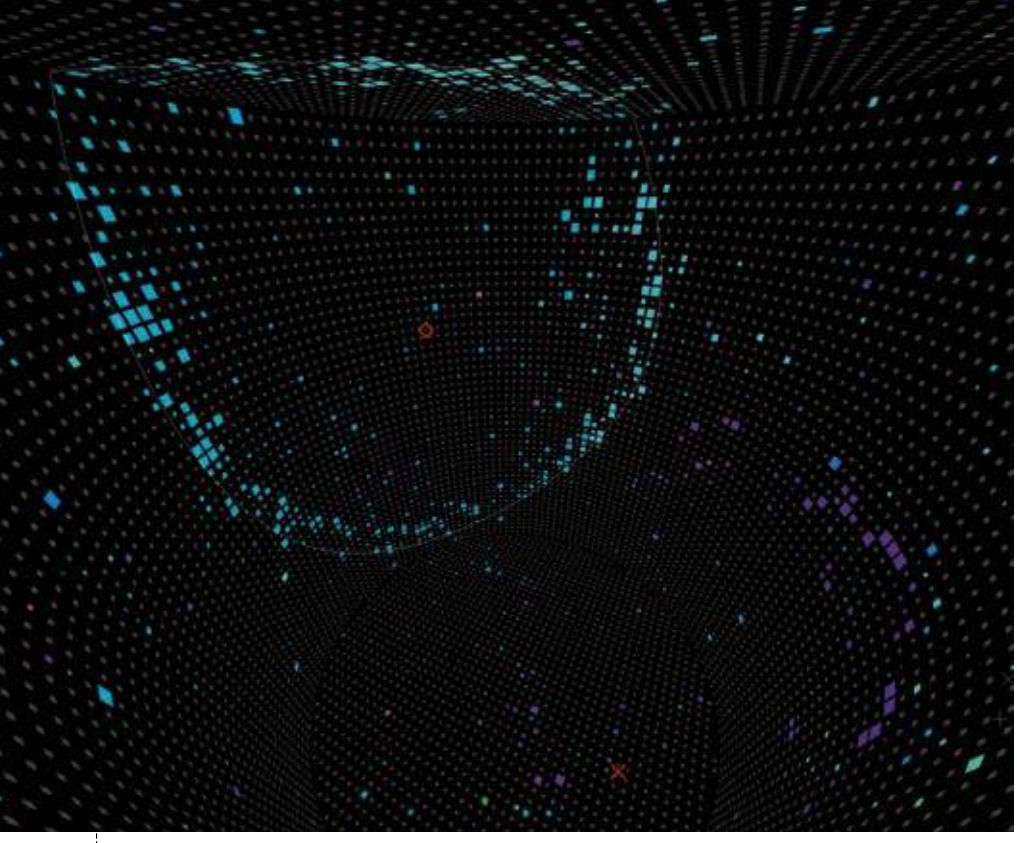
Davis detected only about a third as many electron neutrinos as expected. The mismatch between experimental data and theoretical prediction became known as the Solar Neutrino Problem. It implied one of three things: The experiment was wrong, the standard solar model was wrong, or something spooky happened to neutrinos on their journey from the Sun.

A Japanese team led by Masatoshi Koshiba, Davis' co-Nobelist, discounted the first of these possibilities in 1987. He built a detector named Kamiokande that could register the time of collision events and track the direction of incoming particles. The experiment's results removed any remaining doubt that natural neutrinos originated in the Sun.

Koshiba's experiment also confirmed Davis' discoveries — of both solar neutrinos and the Solar Neutrino Problem — when it recorded the same shortfall of predicted particles. As Koshiba put it, "The experiment was right; the solar model was right. It was the neutrinos themselves which were in some way misbehaving."



AMANDA II'S VIEW of the neutrino sky shows the Northern Hemisphere with neutrinos (produced in Earth's atmosphere) passing through the South Pole's ice and solid Earth. AMANDA-II PROJECT



WHEN A MUON NEUTRINO passed through the Super Kamiokande detector, the event was recorded in this wide-angle computer view. The big light-blue circle shows the flash of Cerenkov light produced by the neutrino, which is traveling faster than the speed of light in water. KAMIOKA OBSERVATORY/UNIVERSITY OF TOKYO/TOMASZ BARSZCZAK

ASTROSPEAK

ANTIMATTER
Matter that has the same properties (such as mass) as ordinary matter, but has an opposite charge; when an ordinary particle and its antiparticle collide, they annihilate each other and release energy in the form of gamma rays.

CERENKOV RADIATION
Blue and ultraviolet light emitted when a high-energy particle (such as a neutrino) moves faster than the speed of light in a medium — ice, water, and even Earth's atmosphere are good examples.

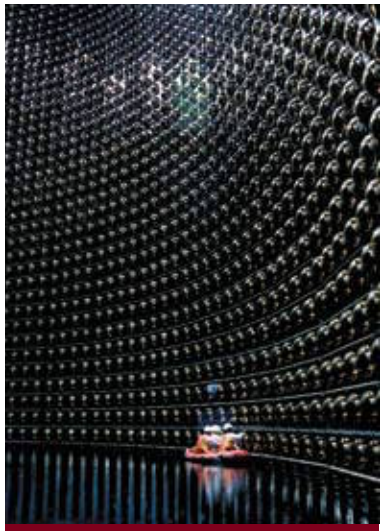
QUANTUM MECHANICS
First introduced by Max Planck in 1900, this theory says that energy is emitted or absorbed in discrete packets, or quanta; the physical laws that describe the behavior of matter at the subatomic level.

Koshiba's group then turned to a hypothesis proposed in 1968 by physicists Bruno Pontecorvo and Vladimir Gribov of the Soviet Union. They hypothesized that electron neutrinos from the Sun might change flavor en route. Such oscillations would reduce the flux of electron neutrinos reaching Earth in favor of other types. Both Homestake and Kamiokande were sensitive only to electron neutrinos, so the working theory was that when electron neutrinos mutated into muon or tau neutrinos while traveling to Earth, they would be missed by the detectors — thus, the observed shortfall.

In 1996, in pursuit of this theory, Koshiba built the Super Kamiokande detector — "super" in that its 50,000-ton water tank was many times larger than its predecessor and employed 11,000 photomultiplier tube sensors. The new equipment's increased sensitivity enabled it to detect the muon flavor of neutrino also, and calculations based on the results confirmed that neutrinos could oscillate between electron and muon types.

Cosmos confounded

With neutrinos' stealthy shapeshifting unmasked, Bethe's theories of stellar furnaces were endorsed resoundingly. While it seems that we now understand how stars work, many larger-scale mysteries remain. Neutrinos could provide the solution to some — or true to form, cause even more cosmic confusion.



SUPER KAMIOKANDE is a cylindrical detector, 130 feet across and 130 feet high, filled with water and lined with light sensors. KAMIOKA OBSERVATORY/UNIVERSITY OF TOKYO

Flavor oscillation is more than just a curious particle phenomenon. If neutrinos oscillate, it implies they must have mass, contrary to Pauli's prediction. Quantum physics theory says the probability of a neutrino changing from one flavor to another depends on the difference in mass between the types. So, if neutrinos are changing type, each type must have a different mass, which means those masses can't be zero. And a non-zero neutrino mass raises all kinds of possibilities.

We have long known the universe contains more matter than we can see — otherwise, galaxies would not have enough mass to hold together. But what makes up this dark matter remains a mystery. Perhaps neutrinos, though tiny, could provide a solution. "We now know that neutrinos constitute about as much mass as all the stars one sees in the night sky," says neutrino physicist John Learned of the University of Hawaii, Manoa. "It could be a lot more. Cosmologists need to take neutrinos into account."

What influence neutrinos have on the universe depends on their exact masses. In the early universe, small wrinkles in the fabric of space evolved into the large structures (galaxies and galaxy clusters) we observe today. Neutrinos, streaming through at nearly the speed of light, helped to iron out these wrinkles. The heavier neutrinos are, the smoother, or emptier, today's universe should look.

Galaxy-mapping surveys, like the recent Anglo-Australian 2dF study, are helping to pin

down neutrinos' masses. By comparing the observed universe's makeup with theoretical models based on different neutrino masses, the 2dF results suggest neutrinos' masses are very small — less than a billionth of a hydrogen atom — and that neutrinos can, therefore, account for only a few percent of the universe's dark matter. Some as-yet-unknown species of particle has to be responsible for the rest.

But if neutrinos can't account for dark matter, perhaps they can explain why matter exists at all. In the Big Bang, matter and antimatter should have been created in equal amounts. When a particle meets its antiparticle, they annihilate each other in a flash of light, so there should be nothing left in the universe except lots of radiation zinging around. The particles that we refer to as matter today were somehow left over after the annihilations. It's highly convenient for us that there was a matter–antimatter asymmetry — because otherwise, we wouldn't exist — but why remains a mystery.

According to Learned, neutrinos may be one of the most promising mechanisms for generating this asymmetry. An ephemeral type of neutrino might decay preferentially into particles rather than antiparticles, if no one minds a bit of rule-breaking. "There could be all sorts of neutrino-like critters," says Learned, "But no matter how complicated the model, there needs to be some hanky-panky somewhere with CP violations."

CP, or charge-parity, symmetry is a rule of nature that says the laws of physics would still hold if every particle were replaced by its antiparticle. It also says the physics of any process and its mirror image are exactly the same. Yet certain particles, including neutrinos, have been observed to disobey this rule.

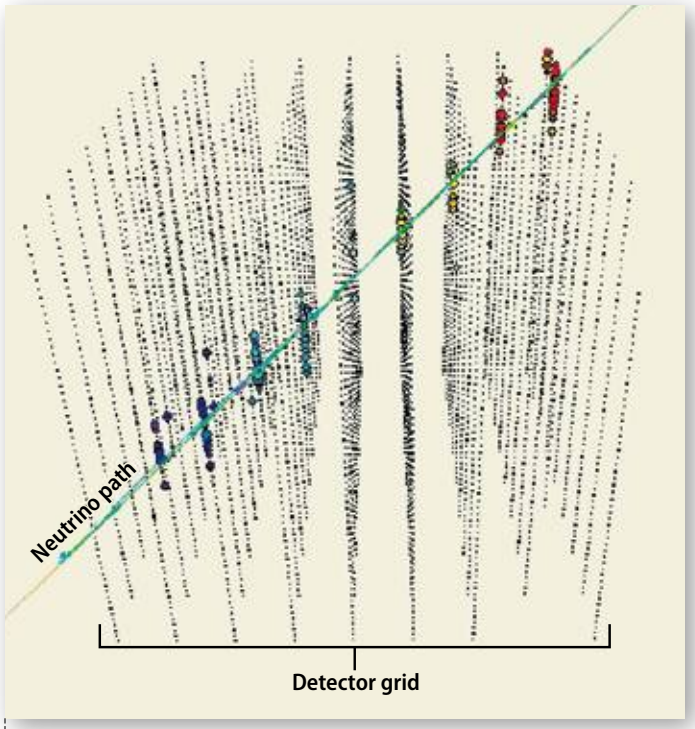
Neutrinos' propensity for mischief makes them elusive. While scientists finally seem to have shown that neutrinos oscillate between flavors, they're now struggling to come up with an addendum to the standard model to account for neutrinos having mass. Neutrinos, which theory describes as having a left-handed spin, also must have a right-handed partner. But how come nobody's spotted it yet?

Particle seesaw

One possibility is that the right-handed neutrino spends much of its time masquerading as a regular neutrino. A leading theory that seeks to combine gravity with the other forces is known as supersymmetry; this theory requires each particle to have a larger, supermassive shadow particle. Each of our three neutrinos could thus spend a tiny fraction of its time as a supermassive right-handed neutrino. Scientists call this the N particle.

If that's not weird enough, an alternative to invoking N particles is even stranger, because it suggests that each ordinary neutrino has a dark doppelgänger that lives in a world outside our own. String theory, which is currently physicists' best hope for a Theory of Everything, describes a universe that has 10 or 11 dimensions, including our three spatial ones. It pictures normal neutrinos and the other standard model particles as trapped in the three-dimensional world, while other dimensions are populated by exotic ghost particles. In this view, a right-handed "sterile neutrino" could roam around the higher dimensions undetected by us, making its presence felt only through the influence of gravity.

NEUTRINOS may be one of the mechanisms responsible for the matter-antimatter asymmetry.



THE ICECUBE "telescope" at the South Pole will comprise 4,800 light sensors buried throughout 1 cubic kilometer of clear ice in order to search for neutrinos. This image simulates the track of a muon neutrino. UNIV. OF WISCONSIN

The neutrino-detection experiment MiniBooNE (because it's the first phase of the Booster Neutrino Experiment) is searching for the dark doppelgänger by seeking evidence that neutrino flavors oscillate between the muon and electron varieties. The mathematics of such oscillations would favor the existence of a sterile neutrino. An experiment at Los Alamos National Laboratory in 1996 indicated muon and electron neutrinos do oscillate, but other researchers have disputed this. MiniBooNE should settle the argument.

"If none of the other evidence changes and if MiniBooNE sees a signal, then the simplest explanation is that there are indeed sterile neutrinos. And that would be really exciting," says project spokesperson Janet M. Conrad.

Much work remains to be done. Current detectors are sensitive only to higher-energy neutrinos. However, the bulk of the Sun's neutrinos lurk at lower energies, which are harder to work with. Detectors have succeeded in studying only about 0.005 percent of the neutrinos the Sun emits. This means only the least elusive neutrinos have been found so far.

Even that, though, is quite a feat, one which ushers Ray Davis, Jr., and Masatoshi Koshiba into the ranks of scientists able to utter the immortal words of Dr. Peter Venkman (played by Bill Murray) in the movie *Ghostbusters*: "We came, we saw, we kicked its ass!"

THE
FIRST
PLANET

The most ancient world yet known was hiding in plain sight. /// BY RAY VILLARD AND ADOLF SCHALLER

Ever since 1991, when astronomers discovered the first planet orbiting a distant star, they have been surprised by what has turned up. Now, with more than 200 such worlds known, the strange variety of extrasolar planets has been confirmed many times over. Astronomers have found planets with highly eccentric orbits, massive planets orbiting next to their parent stars, even planets circling pulsars.

Yet one recent discovery sticks out like a sore thumb. This lone gas giant sets five new records in scientists' quest to uncover extrasolar planets. It ranks as the oldest, the farthest, the first to orbit a tight binary star system, the first located in a globular star cluster, and the only one to reside in a region highly deficient in the heavy elements thought necessary for building planets. It is the one world we know that will have profound implications for our understanding how planetary systems and life arose in the early universe.

The object has been dubbed the "Methuselah Planet." Like the biblical patriarch, it was born not long after the universe's creation and has existed for an enormous amount of time. This planet formed a staggering 13 billion years ago — less than a billion years after the Big Bang — which makes it nearly 3 times Earth's age.

The ancient world lies 7,200 light-years away, in globular cluster M4 in the constellation Scorpius. The planet was already fully formed when our fledgling galaxy was still growing into a vast spiral star city, long before the Sun ever ignited, and even before the first scraps of interstellar gas and dust began to condense into what would become our solar system. Every other extrasolar planet discovered so far dwells in our stellar backyard, within our galaxy's younger disk population of stars.

You also could call this mysterious giant the "Survivor Planet." For the past 13 billion years, the object has managed to stay confined within M4 despite the rough-and-tumble environment of a globular star cluster, where stars swarm around in a nonstop, violent game of interstellar billiards. The planet endured the death of its parent sun and a collision with a binary star system. Following a brief game of stellar musical chairs, the planet now orbits

THE "METHUSELAH PLANET" orbits nearly 2 billion miles (3.2 billion kilometers) from a tight binary system consisting of a pulsar and white dwarf (the brighter of the pair). The group, seen here from the surface of a hypothetical moon, lies in globular cluster M4, although well outside its dense core.
ADOLF SCHALLER FOR *ASTRONOMY*

a binary system that constantly bathes it in blistering X rays from a spun-up neutron star and ultraviolet light from that star's stripped-down white-dwarf companion.

But perhaps the title "Genesis Planet" best characterizes this world because it could represent the first generation of planets that formed in the universe. The first forms of life in the cosmos may have appeared on such early-bloomer planets — and had 13 billion years to evolve. When the first primitive organic chemistry on Earth was trying to self-replicate, advanced life-forms on first-generation planets may have been building starships.

The discovery suggests that early in its history, the universe was more efficient at making planets than astronomers have thought possible. The construction material for planets back then was much more scarce. The Genesis Planet formed around a star that may have had only 5 percent of the heavy-element abundance in our solar system. These heavy elements were scarcer in the early universe because the first "star factories" had just begun forging carbon, nitrogen, oxygen, silicon, and the like in their nuclear furnaces.

This implies that our galaxy could be teeming with more planets than estimated because the process of forming planetary systems may have been common long ago. Even more important: Where there are planets, there could be life.

Location, location, location

In 1999, astronomers first used the Hubble Space Telescope to hunt for planets in globular star clusters. Hubble's unblinking eye watched 34,000 stars in the nearby cluster 47 Tucanae for 8 consecutive days. The researchers tried to detect if any star showed a momentary drop in brightness as a close-orbiting planet passed in front of it, an event called a transit. The astronomers expected to detect at least a few transits because they were monitoring so many stars. Yet, Hubble failed to see a single event.

This fishing trip bolstered the idea that globular clusters might not have formed planets because their stars lack many heavy elements. Surveys reinforced this idea by showing that all the known planet-bearing stars are richer than our Sun in heavy elements. And systems with more of these elements are more likely to have planets.

Ten years before Hubble's search, a pulsar called PSR B1620–26 in M4 first betrayed the Genesis Planet's presence. Timing changes in clocklike radio pulses showed the pulsar has a slight but complex wobble. This indicated that two orbiting objects gravitationally tug on the pulsar. One of the companions, a white dwarf, was identified in the 1990s. But the second glows too faintly to be seen. Astronomers debated its identity for more than a decade.

A FEW BILLION YEARS AGO, the Genesis Planet and its parent star (behind the planet) entered M4's core. This system soon will interact with a bluish neutron star/white dwarf binary (upper left) that stands out from the cluster's solar-type stars and red giants.
ADOLF SCHALLER FOR *ASTRONOMY*

Radio observations of the pulsar showed that the invisible companion's orbit is tipped to the plane in which the white dwarf and neutron star orbit. But astronomers did not know how either orbit was inclined to our line of sight. Therefore, estimates of the invisible object's mass varied widely. If it were more than 13 Jupiter-masses, it would be a brown dwarf, an object that forms like a star but lacks sufficient mass to ignite nuclear fusion.

The planet's orbital tilt was nailed in 2003, when Steinn Sigurdsson of Pennsylvania State University and his colleagues used an archival Hubble survey of M4 to accurately measure the color and temperature of PSR B1620–26's white-dwarf component. This allowed astronomers to deduce both the white dwarf's age and mass. Knowing the mass narrowed the possible tilt angles of its orbit as seen from Earth. This, in turn, allowed astronomers to pin down the Genesis Planet's orbital tilt. They then calculated the object's mass to be a mere 2.5 Jupiter-masses. There was no question: The mystery object unequivocally ranks as an extrasolar planet.

Odd couple

Hubble observations of M4's oldest and coolest white dwarfs made by the University of British Columbia's Harvey Richer suggest the cluster formed in a furious burst of star formation about 700 million years after the Big Bang. Within a few million years of this firestorm, hundreds of short-lived, high-mass stars detonated as supernovae. Some of the supernovae gave birth to rapidly spinning neutron stars and their cousins, pulsars, the collapsed remnants of the massive progenitor stars.

Supernova shock waves and galelike stellar winds eventually blasted away all the cluster's residual gas and dust, squelching any further starbirth. They also probably tore apart some fraction of the protoplanetary disks that surrounded neighboring lower-mass stars.

Back then, a 2.5-Jupiter-mass planet had just started condensing in a disk encircling a solar-mass star at the cluster's periphery. It probably formed at a distance from the star comparable to Jupiter's distance from the Sun. This would have left room for a terrestrial planet to form in the star's "habitable zone," where oceans of liquid water could remain stable for billions of years.

Deeper inside the cluster, pulsars were scattered among the supernova remnants. Many of the pulsars held on to lower-mass binary companion stars. One of these systems was destined to rendezvous with the Genesis Planet and its Sun-like star. But this would have to wait billions of years as the planet and its parent star followed a slow, looping orbit around M4's center.

Only about 2 or 3 billion years ago, just as early single-celled life was enriching Earth's atmosphere with oxygen, the star

THE CIRCLE marks the spot of the binary star system tucked deep inside M4. The system consists of a millisecond pulsar and a white dwarf (which emits most of the visible radiation picked up in this Hubble image) along with the invisible Genesis Planet.

NASA/HARVEY RICHER, UNIVERSITY OF BRITISH COLUMBIA

and planet plunged through the cluster's core like a wayward comet. They barreled toward a binary system containing an ancient neutron star, which had long since spun down and ceased flickering as a pulsar. Gravitational interaction between the two star systems ejected the neutron star's original companion. This "do-si-do" also put the planet in a 1.7-billion-mile (2.7 billion kilometers) orbit around the new stellar couple.

Roughly 500 million years ago, when the first multicelled life was emerging on Earth, the Genesis Planet's original aging parent star ballooned into a red giant. The giant spilled its outer atmosphere onto the neutron star. Robbing momentum from its bulky companion, the refueled neutron star spun up, revving up its rotation speed to that of a kitchen blender. It reawakened as a millisecond pulsar, irradiating the Genesis Planet with a lethal dose of X rays. By spilling its mass onto the neutron star, the giant star slimmed down to a stellar core weighing just 0.35 solar mass. After less than 100 million years, the red giant shrank to a white dwarf with a helium atmosphere.

Today, the neutron star contains about three-quarters of the entire system's mass but measures only several miles across. That gives it a volume just two billionths that of its white-dwarf companion. The system's barycenter, the pivot point between the two co-orbiting stars, lies about a third of the way from the neutron star to the white dwarf. Ironically, this leaves the mass-challenged Genesis Planet as the system's largest object. It contains a volume almost 600 times greater than both of the stars combined.

Astronomer Alan Boss of the Carnegie Institution of Washington sees the discovery as remarkable evidence that the planet-formation process is much more efficient and robust than previously imagined. In the conventional model, dust and gas settle into a disk encircling a newborn star. The dust coagulates to make embryonic cores that gravitationally sweep up additional disk debris and build planets. But the M4 discovery may bolster ideas that more than one recipe can make gas-giant planets. Boss favors a disk-instability mechanism where clumps of gas quickly cool and contract to make Jupiter-size planets. This method avoids the need to build up planets slowly from rocky seed cores.

The bottom line is that the various mechanisms for making planets are not mutually exclusive, and more than one

Ray Villard *is the public information officer at the Space Telescope Science Institute in Baltimore.* **Adolf Schaller** *is an artist living in Gays Mills, Wisconsin.*

GLOBULAR CLUSTER M4 began life some 13 billion years ago as a starburst region. Hundreds of supernovae and their overlapping remnants dispersed the heavy elements necessary to build planets and life, although the Genesis Planet had already formed in M4's outskirts. At lower right in this image, a high-energy jet blasts from the Milky Way's growing core, home to an active black hole. ADOLF SCHALLER FOR *ASTRONOMY*

could contribute to a single planetary system's construction. If true, this suggests that ancient planetary systems could contain rocky, terrestrial-type planets like Earth. It also seems reasonable to assume that ancient gas-giant planets could be circled by systems of solid moons as big as our Sun's terrestrial planets.

Life in a young galaxy

This line of reasoning has far-reaching implications for the abundance of life in space. If enough carbon and other elements existed to make planets, then there should have been enough material for making life as we know it. Astrobiology research during the past 2 decades shows life is aggressive and opportunistic in using basic elements to build complexity. If planets appeared so early in the universe, then life-forms far more advanced than us might exist.

Because the Genesis Planet is a gas giant akin to Jupiter, it has no solid surface and no niche for life as we know it to emerge. But any rocky moons orbiting the planet might have been abodes for life. And there's no reason to think the Genesis Planet was the sole member of its star's solar system. Other gas giants, and even terrestrial planets like Earth or Venus, could have formed, too.

It's not unreasonable to speculate that carbon-based life might have emerged on one of these hypothetical terrestrial worlds. If a stable and long-lived technological civilization arose, it would have had time to anticipate the catastrophic effects of the system's suicide dive into the globular cluster's core. Alien scientists should have realized that the planets would be reshuffled in the binary star collision. They also should have realized the neutron star would fire up and blast any surviving planets with X rays. The approaching doomsday would have required daunting feats of astroengineering to preserve the civilization. This might have led to an interstellar migration from the system. Or perhaps the inhabitants would have tried to colonize the subsurface regions of any suitable moons orbiting the gas giant.

If anyone did live in the Genesis Planet's system, they would have enjoyed a ringside seat to the Milky Way Galaxy's evolution over billions of years. Perhaps M4 alien astronomers using powerful telescopes briefly noted the birth of our solar system. We probably would have been only a passing curiosity for them. Such a civilization would have perused protoplanetary systems innumerable times with their godlike view from above the galaxy's plane. For them, planet birth in our sprawling young Orion spiral arm was not so long ago, in a galaxy not terribly far away.

New insights from ancient

Key answers to the origin and fate of the universe are locked up in nearby stars. /// BY STEVE NADIS

The Internet enables couch potatoes to explore the world without leaving the comfort of their ergonomic chairs. Contemporary astronomers find themselves in a similar position: They can probe key questions in cosmology by studying stars in our own neighborhood, the Milky Way Galaxy. It's another way of probing the distant past — call it cosmology at zero redshift — that can furnish information unattainable through the more traditional cosmological practice of peering far back in time to the universe's edge.

The trick in doing "cosmology with stars," as Michigan State University astronomer Timothy Beers puts it, is to choose old stars lying on the Milky Way's fringe, or "halo," an area far removed from the star-forming regions in the galactic disk. These stellar fossils may be 13 billion years old or more, and thus contain clues about the mix of elements in the early universe. The relative abundance of those elements can tell us about the nature of the earliest stars, the environment in which they were spawned, and the products of the first explosive supernovae that ended their lives.

Finding old stars is just part of the game. The other trick is locating stars whose spectra betray the presence of thorium and uranium — radioactive elements that decay over vast time spans. Astronomers can then do something similar to carbon-14 dating, used so successfully in geology and archaeology, although the astronomical technique must be applied to samples thousands of light-years away that decay over billions of years instead of thousands. This strategy could help pin down the ages of ancient stars, while setting lower limits on the ages of the galaxy and universe.

"We'd like to be able to say, 'Here's what happened in the first billion years,'" Beers says. "Right now, much of that story is uncalibrated, but we may soon be able to attach a clock to it." Using a star-dating approach called cosmochronometry, astronomers hope to address such basic questions as: Where did the elements come from, how and when were they produced, and what were the objects that made them? "If you're interested in the origins of life," Beers says, "you need to understand the origins of the elements required for life."

> "WE WANT TO KNOW how all the things we see today got here." — *Timothy Beers*

Into the halo

Cosmochronometry has a long way to go before it can resolve fundamental issues like these. So far, age estimates derived from the technique have been crude, although advances are being made by observers, theorists, and laboratory investigators.

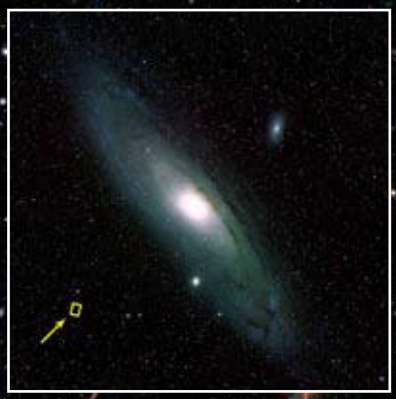
Observations of so-called low-metal halo stars have spurred the recent flurry of activity. Astronomers identify these stars, which include the oldest ever seen, by taking detailed spectroscopic measurements. These spectra reveal a star's "metal" content — the amount of elements heavier than helium. The idea is that immediately after the Big Bang, the only materials available for making stars were hydrogen, helium, and a trace of lithium. Beryllium and boron were produced by cosmic rays, while all heavier elements, from carbon to uranium, were produced by nuclear processes within stars.

The enrichment of the universe has proceeded gradually since the formation of the first stars. To find the oldest stars, investigators look for those with the lowest metal content. The most metal-deficient one spotted to date, HE 0107–5240, has just $1/200{,}000$ the metal content of the Sun. (That's based on the standard measure in the field: the ratio of iron to hydrogen.)

Researchers are becoming adept at identifying elements concealed amid a thicket of spectral lines. University of Texas astronomer Christopher Sneden and his

THE MILKY WAY'S HALO looks much like the Andromeda Galaxy's seen in this Hubble image. Having started to identify ancient stars in our galaxy's halo, astronomers now can learn about the early universe right here at home. ANDROMEDA'S HALO (inset), at least the part imaged by Hubble (box), lies well away from the galaxy's disk and looks nearly empty in this ground-based image.

stars



NASA/ESA/T. M. BROWN (STScI); INSET: BILL SCHOENING/VANESSA MARVEY/REU PROGRAM/NOAO/AURA/NSF

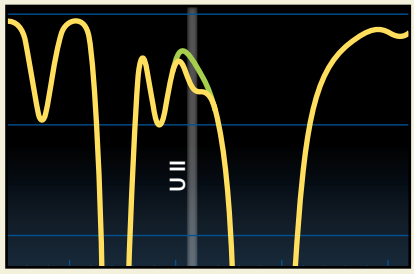
URANIUM BETRAYS NATURE OF ANCIENT HALO STAR

Uranium is the rarest naturally occurring element, so it's no wonder it's difficult to find in a star's spectrum. In fact, until 2001, uranium had never been detected outside the solar system. That changed with observations of the 12th-magnitude star CS 31082–001, an extremely metal-poor object in the halo of the Milky Way Galaxy.

A team of astronomers led by Roger Cayrel of the Observatory of Paris-Meudon took a spectrum of the star with the 8.2-meter Very Large Telescope in Chile. They not only found a line of singly ionized uranium but also 14 lines of thorium, another key element in dating ancient stars. These rare elements showed up because relatively few other lines contaminated the spectrum. The lack of most metals made finding these precious elements possible. — *Richard Talcott*

EUROPEAN SOUTHERN OBSERVATORY

HALO STAR CS 31082–001 (center) appears to be about 12.5 billion years old, making it one of the universe's earliest and an excellent target for cosmochronometry studies.



ASTRONOMY: RICK JOHNSON

IONIZED URANIUM (U II) shows up as a tiny dip in the spectrum of CS 31082–001. If the star didn't have this element, the spectrum would follow the green portion of the curve.

colleagues, for example, measured the abundance of 57 elements in the star CS 22892–052 — that's more elements than have been seen in any star besides the Sun. That's just one indication of how far the state of the art has advanced.

Determining the abundance of elements from a stellar spectrum is a complex art. The starting point is standard absorption spectroscopy: Atoms remove energy from light at characteristic wavelengths, leaving dark absorption lines in the spectrum. Each atom produces a distinctive pattern of lines. Astronomers rely on models of spectra for stars at a given temperature and metal abundance. "That tells you what you should see — a model version of the spectrum," explains Beers. Researchers then compare the predicted strengths of the absorption lines with those observed. From this, they deduce the amount of light removed from the spectrum and, thereby, infer an element's abundance.

For chronometry, the more elements that can be measured, the better, but distinct lines of thorium and uranium are especially helpful. Choosing the right radioactive isotope for your "clock" is critical, because you don't want an element that decays too quickly. Time frames are long in cosmology, and accurate measurements require sufficient quantities of the material to last billions of years. Thorium-232, with a half-life of 14.1 billion years, and uranium-238, with a half-life of 4.5 billion years, surely qualify.

In 2001, Roger Cayrel from the Observatory of Paris-Meudon and his collaborators unveiled the first measurements of thorium and uranium in a metal-poor star, CS 31082–001. Since then, two other stars with discernible thorium and uranium lines have been reported. "The importance of having abundances of both thorium and uranium in a single star cannot be overstated," says Sneden. Because the two elements have different decay rates, the thorium-to-uranium abundance ratio changes in a predictable way — making it a sensitive indicator of a star's age.

The general strategy is to measure the relative abundance of thorium and uranium as seen in stars today and compare that with the initial abundance ratio. Knowing the difference between these two ratios and how fast these elements decay, astronomers can easily deduce a star's age. Figuring out the initial ratio, however, is far from simple. It's tied up with questions about the origins of heavy elements — a long-standing cosmological puzzle.

Creating the elements

Astronomers have little doubt that nuclear fusion in stellar cores creates the elements carbon through iron. Elements with higher atomic numbers (30 and up) form through "neutron capture."

In this process, an atomic nucleus absorbs additional neutrons. These extra neutrons don't change the element — an element is defined solely by the number of protons in its nucleus (its atomic number). However, neutron capture is followed by beta decay, a radioactive process that converts a neutron into a proton, an electron, and an antineutrino. The electron and antineutrino are ejected from the nucleus, while the proton stays behind.

Neutron capture assumes two forms, occurring either slowly (the s-process) or rapidly (the r-process) compared with how long it takes the new nuclei to beta decay. Each process contributes roughly half the total elements.

The s-process shuts off at element 83, bismuth. All heavier elements, thorium and uranium included, are made by the r-process. The r-process created the first heavier-than-iron metals in the Milky Way, so those are the ones observed in the oldest stars. S-process elements did not emerge until later in the galaxy's history.

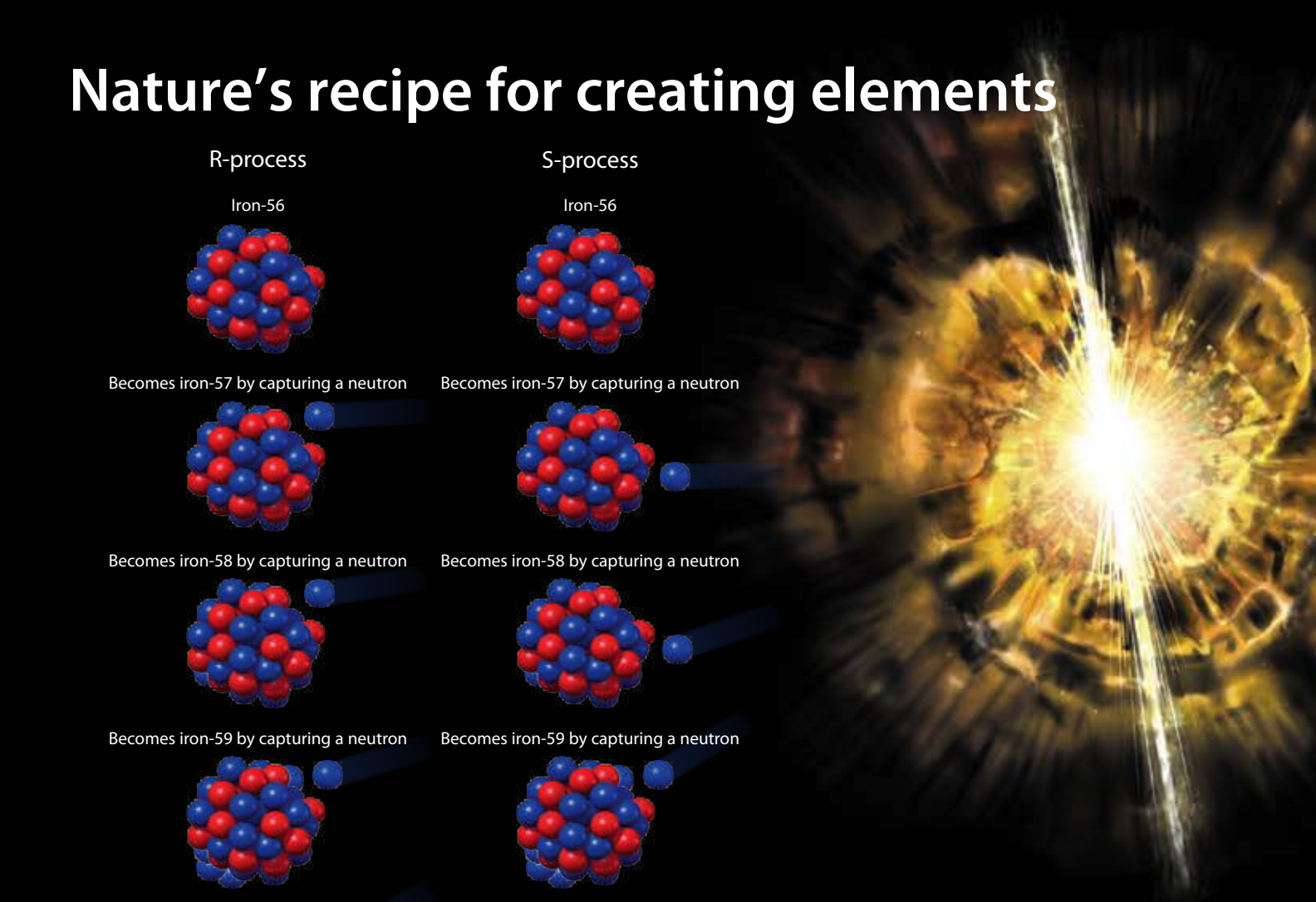
Models for the s-process work well. "That's because we're dealing with nuclei that are either stable or have long half-lives," explains University of Oklahoma astrophysicist John Cowan. "We've been able to measure their properties in the lab for decades."

The r-process, on the other hand, is shrouded in mystery. The wildly unstable nuclei that give rise to elements like uranium and thorium are so exotic, adds Michigan State physicist Hendrik Schatz, they've never been created in the lab. "We barely know anything about them."

Researchers have yet to identify the astrophysical setting where r-process elements are made. Mergers of neutron stars were once a leading candidate, but theorists now believe mergers proceed too slowly, putting the scenario at odds with recent observations of low-metal stars.

Steve Nadis *is a science writer and frequent* Astronomy *contributor who lives in Cambridge, Massachusetts.*

Nature's recipe for creating elements



R-process

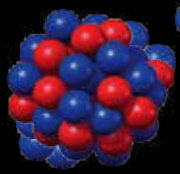
Iron-56

Becomes iron-57 by capturing a neutron

Becomes iron-58 by capturing a neutron

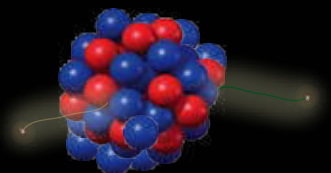
Becomes iron-59 by capturing a neutron

Becomes iron-60 by capturing a neutron



Becomes iron-61 by capturing a neutron

Iron-61 decays
A neutron gets converted into a proton, an electron, and an antineutrino



Becomes cobalt-61

S-process

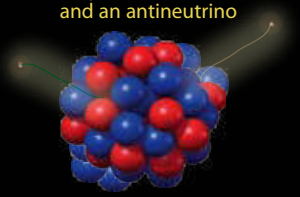
Iron-56

Becomes iron-57 by capturing a neutron

Becomes iron-58 by capturing a neutron

Becomes iron-59 by capturing a neutron

Iron-59 decays
A neutron gets converted into a proton, an electron, and an antineutrino



Becomes cobalt-59

proton

neutron

electron

antineutrino

The universe began as a dull place — lots of hydrogen and helium, but little else. Things began to grow interesting after the first stars formed. These ancestors of the stars we see today fused hydrogen into helium in their cores. Later, they and their offspring created more complex atoms, including carbon, oxygen, and nitrogen.

The heaviest stars forged ever more exotic elements, up to iron-56 (a nucleus containing 26 protons and 30 neutrons). But that's as far as fusion goes. Creating heavier elements requires an influx of neutrons. Let's look at how stars turn iron-56 into isotopes of cobalt. The same methods produce heavier elements as well.

Deep inside evolved stars, nuclear reactions create lots of neutrons. When iron-56 captures a neutron, it becomes iron-57. Another capture produces iron-58, and another iron-59. Each neutron capture takes about a year — so scientists dub this the s-process (for slow). Iron-57 and iron-58 are fairly stable, but iron-59 decays to cobalt-59 in a month, before it can capture another neutron.

To get past this roadblock, you need a high flux of neutrons, like that found in supernovae. Iron-59 adds one neutron to make iron-60 and a second to form iron-61. That then decays to stable cobalt-61. Scientists call this the r-process because it happens so rapidly. The same process creates the heaviest elements. — *R. T.*

ASTRONOMY: RICK JOHNSON

The best guess is that the r-process occurs more commonly within supernovae, says Cowan, "but the place within a supernova cannot be pinned down because we don't know the details of the explosion." Many questions remain: What is the mass of the supernova's progenitor star? After the star collapses, triggering the explosion, where is the r-process material made and ejected? How many neutrons are needed to sustain the r-process?

Despite these quandaries, astronomers have managed to construct r-process models that work surprisingly well. To get around the explosion specifics, researchers separate their calculations from the supernova. "Essentially, we say somewhere in the universe a lot of neutrons are made," Schatz explains. "We take a seed nucleus like iron and try to guess the neutron flux and other conditions that would produce all the stable elements in the proportions seen today."

The next step is to see how much thorium and uranium the model predicts. The abundances of these and other elements form a starting point for the chronometer.

On the trail of ancient stars

Following this approach, Cayrel's team estimated the age of CS 31082–001 at 12.5 billion years, give or take 3 billion. Sneden's team arrived at an estimate of 14.2 billion years (plus or minus 3 billion) for CS 22892–052.

Of course, a star can't be older than the galaxy or universe it resides in. This means estimates derived from cosmochronometry, if credible, establish lower bounds on the age of the galaxy and universe.

Star-dating offers a potential advantage because it relies on direct measurements that are independent of age calculations based on cosmic microwave background studies, like those made by the Wilkinson Microwave Anisotropy Probe (WMAP). "The answer you get from chronometry doesn't depend on the assumptions you make about cosmology," Cowan says.

So far, chronometry points to a universe that's roughly 13 to 14 billion years old — consistent with WMAP's findings and reassuring to practitioners in the field. But the point, says Harvard astronomer Lars Hernquist, is not just to get a single number like the age of the universe. "WMAP gives you precise measurements of the *average* properties of the universe, but it can't tell you how things evolved after the cosmic microwave background was released," Hernquist explains. "This approach, on the other hand, can provide the details, mapping out the history of star and galaxy formation."

Measurements of element abundance ratios in old stars, according to University of Chicago cosmologist Jason Tumlinson, provide strong clues about the size of the universe's first stars. A 2004 analysis by Tumlinson and his colleagues suggests the oldest stars were enriched by supernovae whose progenitor stars weighed between 10 and 140 solar masses. This model fits well with both WMAP results and the latest observations of halo stars, he says.

Knowing exactly when the first stars formed, according to Hernquist, could reveal the nature of dark matter — the mysterious stuff that makes up nearly one-quarter of the universe's mass-energy content and far outweighs normal matter.

Stars would have formed earlier if dark-matter particles are about as massive as a proton and move slowly (cold dark matter), whereas star formation would have been delayed if dark matter is lighter and moves faster (warm dark matter). WMAP can't

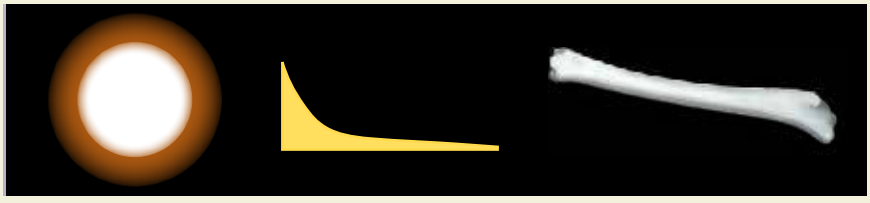
OLD BONES AND AGED STARS — DATING RELICS OF THE PAST

It may surprise you that astronomers seeking the age of the oldest objects in the cosmos use the same technique as archaeologists pinpointing the age of ancient human bones. Welcome to the world of radioactive dating.

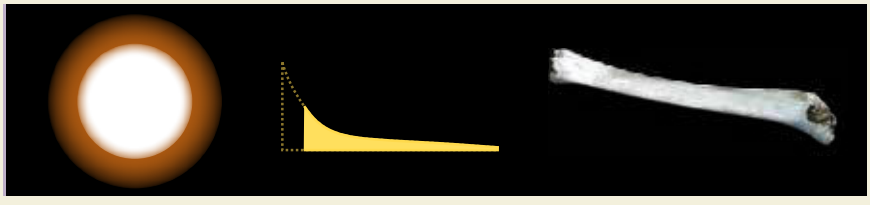
The approach works because every radioactive element decays at a set rate, known as its half-life. Gather enough atoms together, and you can say with certainty that half the existing atoms will decay in the given time.

To measure long periods, like the age of the first stars, you need a long-lived element. Astronomers use uranium-238, which decays to lead-206 with a half-life of 4.47 billion years, and thorium-232, which decays to lead-208 with a half-life of 14.1 billion years.

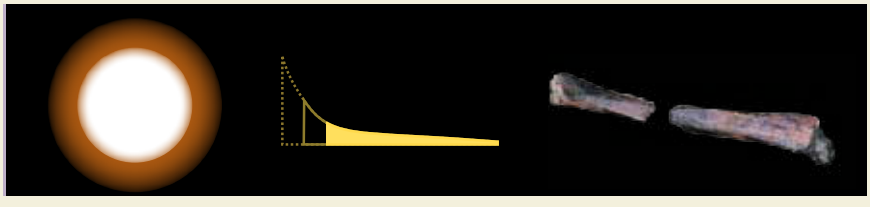
Archaeologists usually want to date bones or other artifacts thousands of years old. Carbon-14 is the perfect isotope. It decays to nitrogen-14 with a half-life of 5,730 years. — *R. T.*



AT THE GALAXY'S BIRTH, a star (left) would hold only traces of uranium and thorium. Astronomers want to know when the star formed. Archaeologists want to learn the age of a human ancestor. Fortunately, bones (right) stop absorbing carbon-14 at death.



AFTER ONE HALF-LIFE of uranium-238, the star doesn't look much different. One half-life of carbon-14 has affected the bone more noticeably. A graph (middle) shows the percentage of remaining atoms for each radioactive element looks exactly the same.



ANOTHER HALF-LIFE goes by and the star looks the same — although the galaxy has given birth to our solar system. The bone looks much worse for wear. Yet the radioactive elements in both tell the same story, with just one-quarter of the original amount left.

ASTRONOMY: RICK JOHNSON

differentiate between the two scenarios, says Hernquist, but the age-dating of metal-poor stars might.

Nevertheless, chronometry cannot shed much light on questions like this until astronomers greatly reduce the method's error bars — currently an ample 3 billion years. About half the uncertainty lies on the observational side, the other half in theory, Schatz says. On the theoretical end, the biggest uncertainty remains our limited knowledge of the r-process.

The future is near

Schatz hopes to make headway through experiments at the National Superconducting Cyclotron Laboratory (NSCL), based at Michigan State University, and a more ambitious facility, the Rare Isotope Accelerator (RIA), slated for operation in 2012 at a site to be named. High-speed nuclear collisions at NSCL can produce lightweight r-process elements, but RIA's higher-intensity beam should create the majority of r-process elements. "That should put most of the r-process on a solid experimental footing," claims Schatz. Still, RIA will not create the direct progenitors of uranium and thorium. "There will still be some extrapolation," he admits, "but it will take a much smaller leap."

On the observing end, astronomers are combing the galaxy's halo for stars with ever lower metallicity, ideally ones that also contain strong lines of uranium and thorium. Most spectroscopic measurements to date have been in the visible spectrum, but Cowan believes ultraviolet observations are critical. That's why he, Sneden, and Beers propose pointing the ultraviolet-sensitive Hubble Space Telescope at halo stars.

How accurate can chronometry get? The WMAP team claims the universe is 13.7 billion years old, accurate to within 1 percent. "I don't think we'll get close to 1-percent accuracy in the foreseeable future," says Cowan, "but there are still opportunities for dramatic improvement." To some extent, it's a question of numbers: Once the distribution of elements is known for a large population of halo stars over a broad range of metallicities, chronometry will begin to furnish reliable age estimates.

So far, researchers in the field have had limited data to work with, but Beers expects the floodgates will open soon. By the time the second phase of the Sloan Digital Sky Survey (SDSS) is complete in 2008, he and his colleagues should have access to spectral data on 50,000 stars, 5,000 of which are likely to be ancient, low-metal ones.

What's more, a phase-two component of SDSS, called the Sloan Extension for Galactic Understanding and Exploration, could revolutionize stellar astronomy. In 2 years, it should capture spectra for 250,000 stars, including 50,000 low-metal ones.

Once astronomers have spectral measurements for thousands of halo stars at their disposal, the fun should really begin. And, more importantly, a clearer picture should emerge.

A big part of cosmology, Beers says, is figuring out what the universe is made of and where the elements came from. "The story is unsatisfying right now because it doesn't have a beginning. We want to know how all the things we see today got here." If Beers and his fellow scientists are right, answers will come from the study of metal-poor stars.

"Having nearby stars that can transport us to the early universe is a gift from nature that's almost too good to ask for," says Tumlinson. It's easy to imagine that no stars would have survived from that epoch, leaving no direct evidence for us to examine. Despite our good fortune in having these stars as neighbors, it has taken human ingenuity, not luck, to elicit their secrets.

CRASH-TESTING ATOMIC NUCLEI IN THE LABORATORY

To get a better handle on cosmochronometry, scientists need to understand the r-process better. The National Superconducting Cyclotron Laboratory produces many rare r-process nuclei.

The technique: Accelerate a stable nucleus to 60 percent of the speed of light and then smash it into a target. The target's composition and thickness determine which isotopes the impact creates. — *R. T.*

MICHIGAN STATE UNIVERSITY

THE A1900 SEPARATOR at the National Superconducting Cyclotron Laboratory creates lightweight r-process elements, helping scientists understand this vital process.

The star-splitting JETS of supernovae

To explain the existence of unusually energetic supernovae and gamma-ray bursts, astrophysicists invoke jets of matter moving at nearly the speed of light. /// BY FRANCIS REDDY

Recent discoveries confirm a long-suspected link between two of the most energetic phenomena in the universe: exploding stars, called supernovae, and long-duration gamma-ray bursts — those lasting more than 2 seconds. Gamma-ray bursts (GRBs) occur at a rate of about one per day and were first recognized in the 1970s. But the first compelling evidence linking them to stellar explosions came April 25, 1998, when astronomers found an unusually powerful supernova, designated SN 1998bw, at the position of a long-duration burst. That event, called GRB 980425, didn't clinch the connection, however, because the burst was strangely weak, only $1/10{,}000$ as energetic as other long bursts for which distances were known.

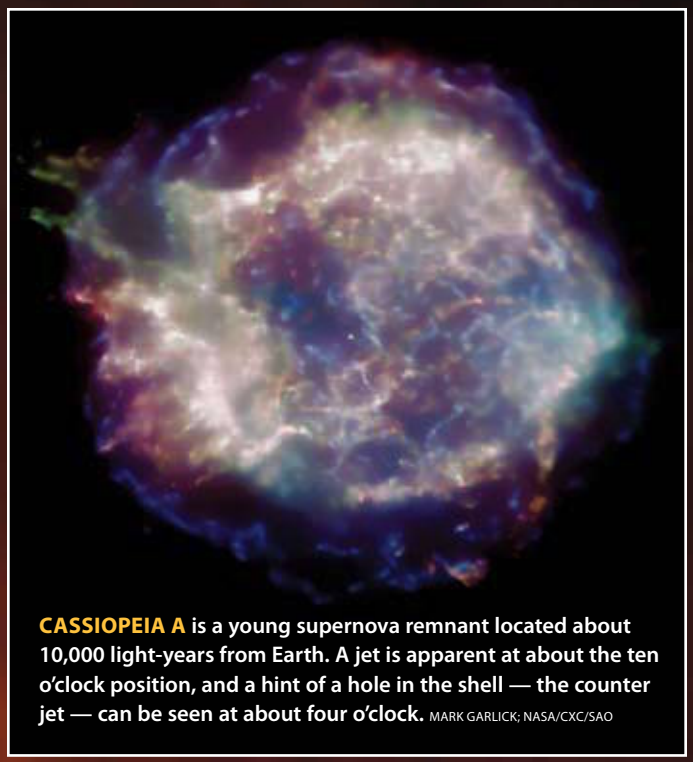
Circumstantial evidence connecting the bursts to supernovae mounted in the following years. GRBs seemed to be associated with areas of active star formation; this was consistent with the short lives of massive stars thought to be supernova candidates. Transient patches of light — called optical afterglows — found at some GRB positions sometimes exhibited "bumps" in brightness after a few days; occasionally, hints of supernova-like features emerged as the afterglow faded. Many astronomers suspected they were seeing the gradual rise to maximum light of a supernova.

"And that convinced more people, but not everybody," says Stan Woosley, an astrophysicist at the University of California, Santa Cruz. "What we really wanted was a supernova we could identify with an ordinary GRB."

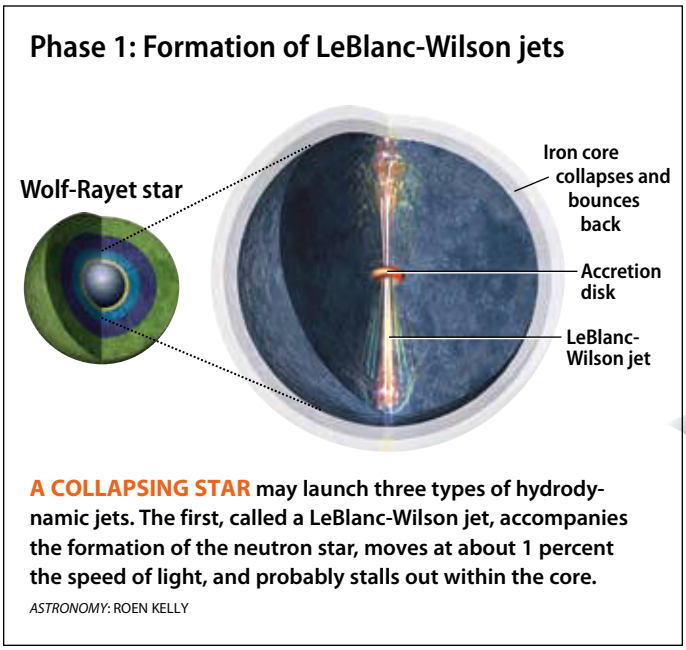
JETS BLASTING from the center of a collapsing star give rise to gamma-ray bursts. Earlier, less-energetic jets may help explode the star as a supernova. *ASTRONOMY:* ROEN KELLY

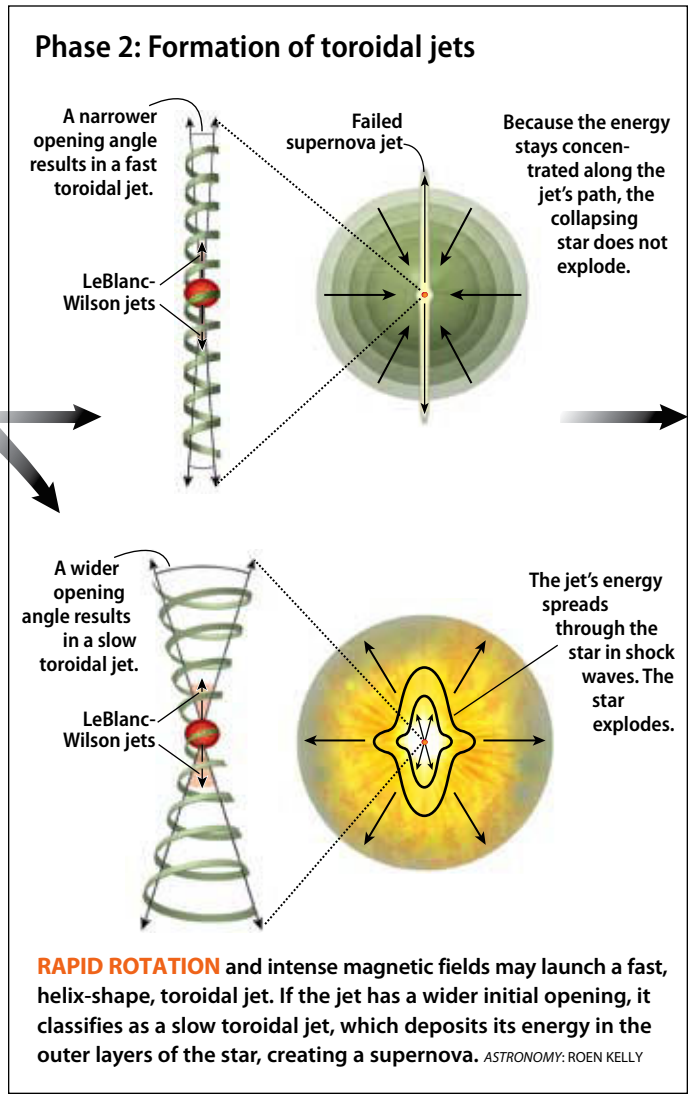
Confirmation

A supernova/GRB combination was just what they got March 29, 2003, when NASA's High-Energy Transient Explorer II satellite locked onto a burst in the constellation Leo. For 25 seconds, GRB 030329 outshone everything in the universe at gamma-ray wavelengths. Ninety minutes later, astronomers at Siding Spring Observatory in Australia found its afterglow, still more than a trillion times brighter than the Sun. Within a day, a detailed spectrum obtained at Paranal Observatory in Chile showed that the burst was located 2.65 billion light-years away, making it the second-nearest long-duration GRB



CASSIOPEIA A is a young supernova remnant located about 10,000 light-years from Earth. A jet is apparent at about the ten o'clock position, and a hint of a hole in the shell — the counter jet — can be seen at about four o'clock. MARK GARLICK; NASA/CXC/SAO


Phase 1: Formation of LeBlanc-Wilson jets
Wolf-Rayet star
Iron core collapses and bounces back
Accretion disk
LeBlanc-Wilson jet
A COLLAPSING STAR may launch three types of hydrodynamic jets. The first, called a LeBlanc-Wilson jet, accompanies the formation of the neutron star, moves at about 1 percent the speed of light, and probably stalls out within the core.
ASTRONOMY: ROEN KELLY


Phase 2: Formation of toroidal jets
A narrower opening angle results in a fast toroidal jet.
LeBlanc-Wilson jets
Failed supernova jet
Because the energy stays concentrated along the jet's path, the collapsing star does not explode.
A wider opening angle results in a slow toroidal jet.
LeBlanc-Wilson jets
The jet's energy spreads through the star in shock waves. The star explodes.
RAPID ROTATION and intense magnetic fields may launch a fast, helix-shape, toroidal jet. If the jet has a wider initial opening, it classifies as a slow toroidal jet, which deposits its energy in the outer layers of the star, creating a supernova. ASTRONOMY: ROEN KELLY

ever detected. (GRB 980425, which was 140 million light-years away, remains the closest.) The proximity of GRB 030329 resulted in a bright afterglow emission, permitting the most extensive follow-up observations to date. On April 7, a team led by Thomas Matheson of the Harvard-Smithsonian Center for Astrophysics announced that spectral lines characteristic of a supernova were emerging from the burst's afterglow. Astronomers quickly confirmed the observation and designated it SN 2003dh.

Some called the event a watershed for high-energy astrophysics and likened it to a cosmic Rosetta Stone. "I think today it is absolutely certain that some subset of gamma-ray bursts are made when massive stars die and that the bursts are accompanied by supernova explosions," Woosley says.

Astronomers immediately were struck by similarities between SN 2003dh and SN 1998bw. Both were classified as type Ic supernovae — massive, particularly energetic stars expanding at more than twice the speed of ordinary supernovae. The expansion of SN 2003dh was measured at 22,000 miles per second (36,000 kilometers per second), the fastest of any observed supernova. Such energetic events once were called "hypernovae," but many consider this term poorly defined and no longer use it.

SUPER TERMS FOR SUPERNOVAE

ACCRETION DISK
A disk of visible material collected by, orbiting, and falling into a black hole.

AFTERGLOW
Lower-energy wavelengths (radio, optical, X rays) produced after a gamma-ray burst that can linger for months.

ASYMMETRICAL SUPERNOVA
Any supernova whose material is not distributed evenly (spherically).

DIFFERENTIAL ROTATION
The motion of a non-solid object where different areas spin at different speeds.

PULSAR
A rotating neutron star with a bright spot or spots that moves past our line of sight, creating a pulse.

STELLAR WIND
Charged particles, mainly high-energy electrons and protons ejected from a star's upper atmosphere; the Sun's solar wind creates aurorae.

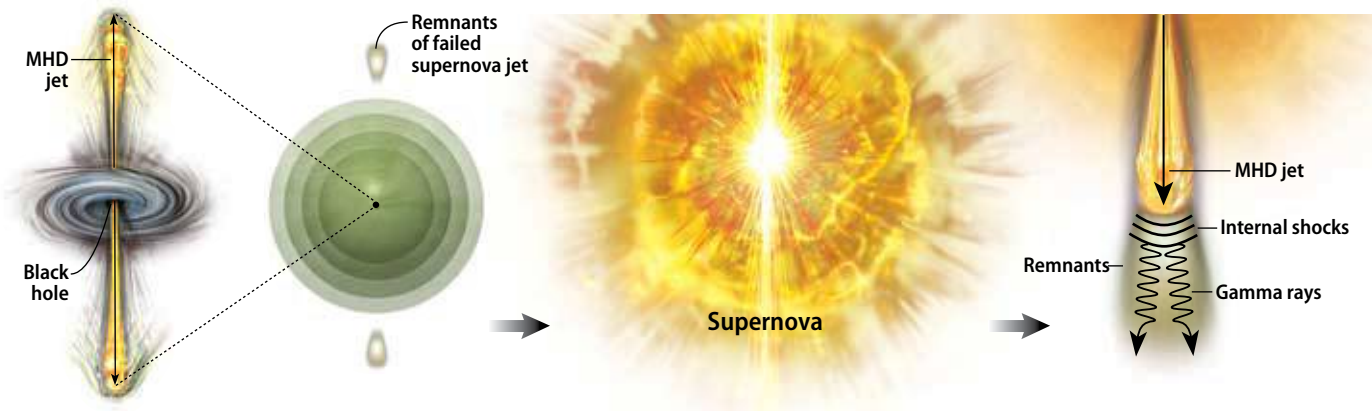
What was it?

The best fit with our understanding of GRBs is the "collapsar" model introduced by Woosley in 1993, which predicted an observational link between long GRBs and supernovae. Three essential components must be present: a particular type of massive star, called a Wolf-Rayet star; a rotating stellar core; and a core collapse that fails to produce a successful supernova, resulting in a black hole at the center of the star.

Wolf-Rayet stars begin their lives with masses more than 20 times that of the Sun. They lose about two-thirds of that mass during their short, hot lives, either by vigorous stellar winds or through interactions with a nearby companion star. A typical star in Woosley's calculations begins life with 30–35 solar masses. After 5 or 6 million years, its hydrogen envelope is gone, and its mass has dropped to perhaps 10 or 12 Suns. On the inside, the star has taken on the layered structure characteristic of advanced stellar evolution. The star supports itself against collapse by running through a

Francis Reddy *is an associate editor of* Astronomy.

Phase 3: Core-collapse supernova and gamma-ray burst



A THIRD JET — called a magnetohydrodynamic (MHD) jet — may form if the neutron star is highly magnetized and rapidly rotating. Another process may create an MHD jet — if a black hole with an accretion disk forms (as in the collapsar model).

An MHD jet moves outward from the star's core at nearly the speed of light and interacts with material ejected by slower jets. According to one theory, internal shocks from such collisions create a gamma-ray burst. *ASTRONOMY*: ROEN KELLY

succession of nuclear fuels, a process that culminates with a core filled with iron-group elements. At that point, the process can no longer continue. The star's surface now lies far out in the extended atmosphere formed by its strong stellar wind and is several times larger than our Sun. From the outside, observers would see a star with a spectrum rich in helium, carbon, and oxygen, a stellar wind of 3.25 million mph (5.4 million km/h) or faster, and a surface temperature around 50,000 K.

When the core of the star collapses, it fails to trigger a shock wave capable of blowing the star apart. Within a second, a black hole of 3–4 solar masses forms. The collapse magnifies the rotation speed of the star. This increases the centrifugal force and slows the infall of matter along the star's equator. This matter then piles up into an accretion disk around the black hole. But nothing resists the collapse along the star's spin axis, and, during the next few seconds, matter raining down toward the black hole evacuates a path through the star. "There's a density contrast of at least a thousand between the poles and the equator now," Woosley says.

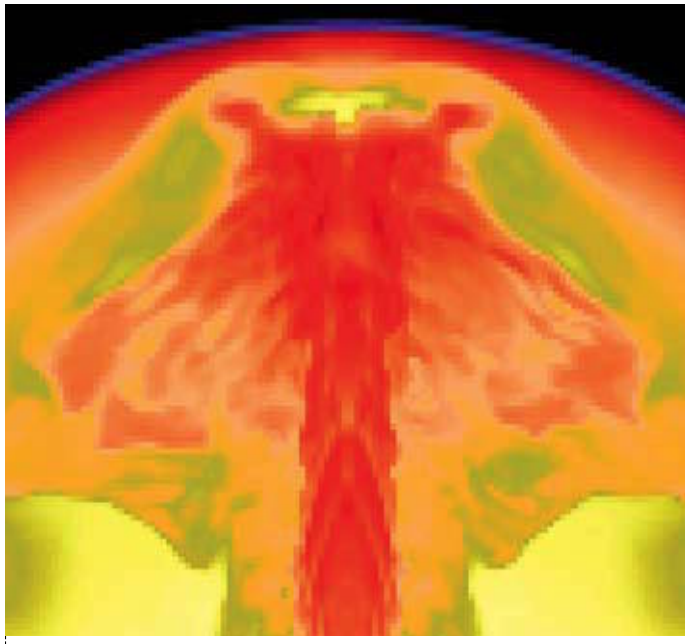
A powerful magnetic field quickly arises from the dynamo created by the spin of the black hole and the differential rotation of its accretion disk. This field accelerates matter outward along the path of least resistance. A small amount of stellar material blasts out along the star's spin axis moving at 99.5 percent the speed of light. About 6–8 seconds after this jet breeches the star's surface, the jet expands outward and accelerates to 99.999 percent the speed of light. "No bulk matter moves faster in the universe except the nuclei in cosmic rays," Woosley says.

The core of the jet has a small mass, only about a hundred-thousandth that of the Sun, but it contains tremendous internal energy. When the jet breaks out of the star, blobs of its fastest-moving matter interact with one another and emit the gamma rays we detect as a GRB.

Both theory and observation suggest the emerging jet typically has a radius of about 4°, so we see a GRB only when a jet happens to be directed toward Earth. Woosley estimates that for each burst astronomers observe, some 500 remain undetected.

The jet continues outward and interacts with the star's extended atmosphere, energizing the gas so that it gives off radio waves, light, and X rays — radiation astronomers observe as afterglow emission. Meanwhile, an asymmetric supernova has begun. Portions of the star neither ejected in the jet nor captured in the black hole expand rapidly along the rotational axis and more slowly along the equatorial plane.

"As recently as 5 years ago there were more than 100 models for gamma-ray bursts. Now it's narrowed down to two," Woosley says.



A SUPERNOVA JET breeches the surface of a collapsing Wolf-Rayet star at nearly the speed of light in this simulation. Red and orange indicate higher densities. When the jet exits the star, gamma rays produced in its fastest-moving material create a GRB, which will be visible if the jet points toward Earth. WEIQUN ZHANG, STAN WOOSLEY (UCLA, SANTA CRUZ) AND ALEXANDER HEGER (LOS ALAMOS NATIONAL LABORATORY)

BEFORE THE FALL: INSIDE A WOLF-RAYET STAR

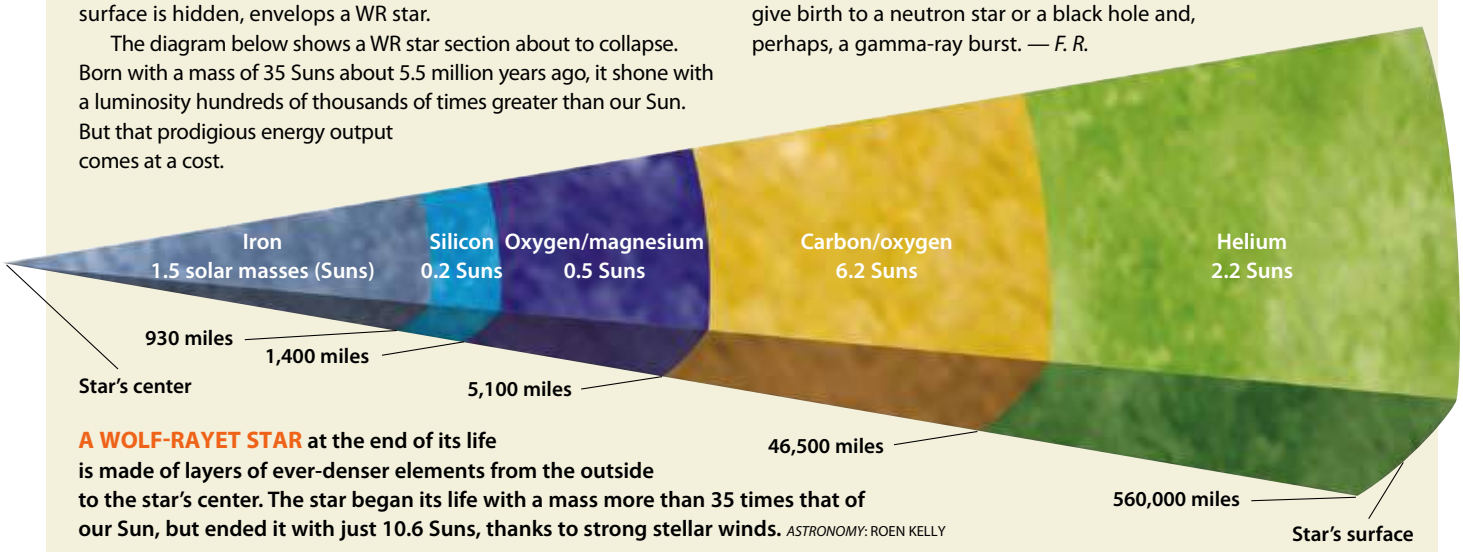
The collapsar model for gamma-ray bursts requires a specific type of star known as a Wolf-Rayet (WR) star. French astronomers Charles Wolf and Georges Rayet first identified this type of star in 1867 by studying a visual spectrum. Wolf-Rayet stars are rare — only 226 have been identified in our galaxy.

WR stars have masses at least 20 times that of the Sun and surface temperatures between 30,000 K and 60,000 K. Violent stellar winds of more than 3.25 million mph (5.4 million km/h) quickly bleed off the star's outer layers. WR stars may lose more than two-thirds of their mass during their lifetimes. The expulsion of so much gas means that an "atmosphere" larger than the star, whose actual surface is hidden, envelops a WR star.

The diagram below shows a WR star section about to collapse. Born with a mass of 35 Suns about 5.5 million years ago, it shone with a luminosity hundreds of thousands of times greater than our Sun. But that prodigious energy output comes at a cost.

The star rapidly depleted the hydrogen fuel supply in its core and collapsed, producing energy by fusing helium, the by-product of hydrogen fusion. Meanwhile, vigorous stellar winds blew away most of the star's original mass.

After a few hundred thousand years, the star needed a new fuel source, this time carbon. The process of fusing heavier elements is one of rapidly diminishing returns. It took only months to require a new fuel — oxygen, then neon. Finally, silicon began to fuse, filling the core with iron-group elements. But that was the end of the line — iron fusion liberates less energy than it consumes. The star quickly collapsed and exploded as a supernova. The remnant will give birth to a neutron star or a black hole and, perhaps, a gamma-ray burst. — *F. R.*



A WOLF-RAYET STAR at the end of its life is made of layers of ever-denser elements from the outside to the star's center. The star began its life with a mass more than 35 times that of our Sun, but ended it with just 10.6 Suns, thanks to strong stellar winds. *ASTRONOMY*: ROEN KELLY

Do GRBs always require a black hole or can an exceptional, highly magnetized, rapidly rotating neutron star also do the job? "This is the level at which we now argue," he says.

"My personal bet is that the GRBs do represent black-hole formation," says J. Craig Wheeler of the University of Texas, Austin. He argues there exists no direct observational evidence for black-hole formation, only that large energies, velocities near the speed of light, and directional flow of jet material are involved.

Wheeler notes that our knowledge of how a collapsing stellar core turns into an expanding supernova is preliminary at best. He says new evidence — and a fresh look at old evidence — suggests that lower-energy jets may play an important role in many, if not most, supernovae.

For example, detailed optical studies of the supernova remnant known as Cassiopeia A revealed a multi-jet structure, part of which was imaged by the Chandra X-ray Observatory in 1999. In addition, elongated ejecta have been found in the remnant of SN 1987a, the first supernova visible to the unaided eye in 400 years.

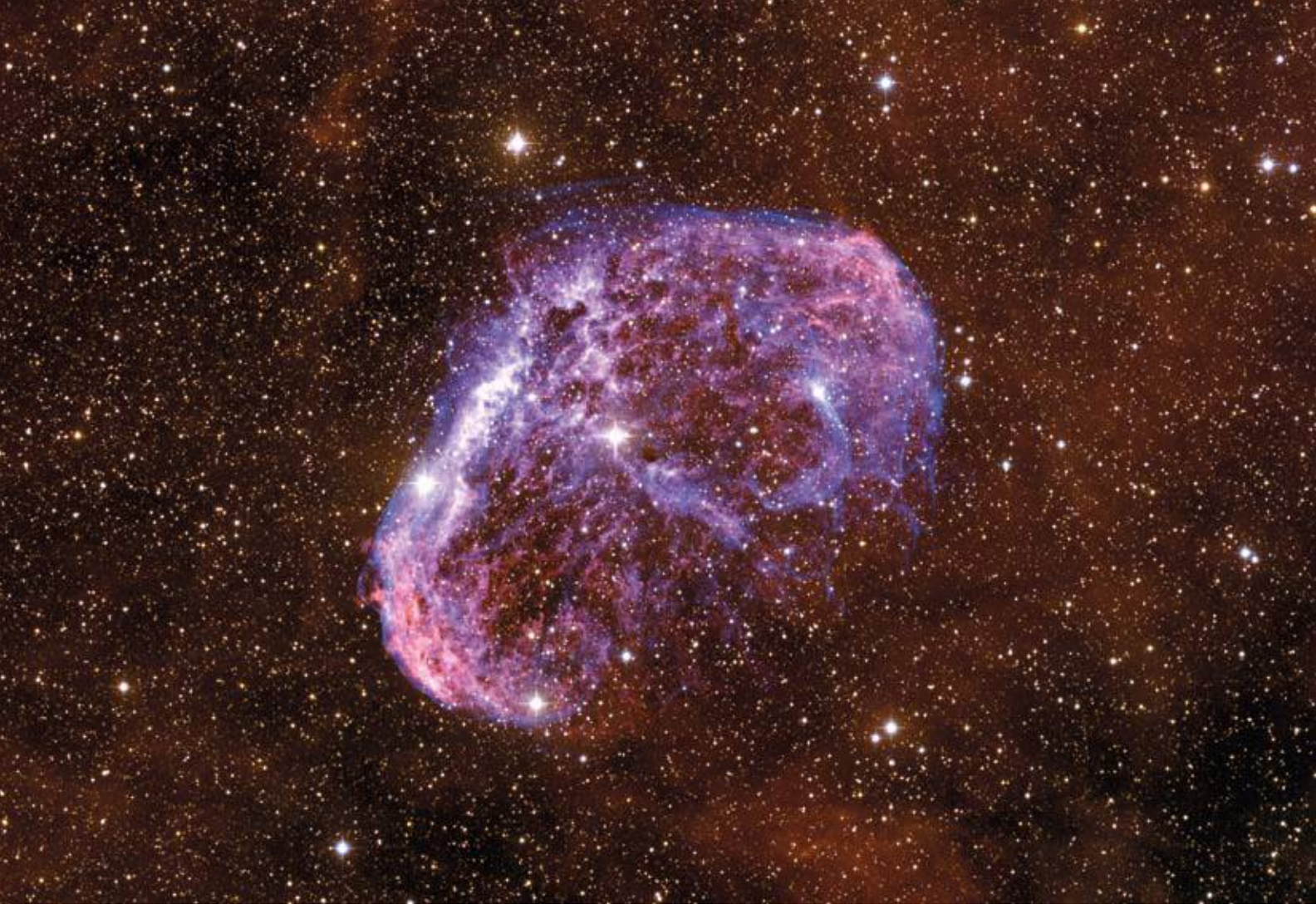
Moving right along

Another line of evidence for asymmetrical supernovae is the curiously high space velocities of pulsars and neutron stars. The Crab and Vela pulsars move at about 216,000 mph (360,000 km/h), a speed that might be explained by the breakup of a binary star system and the subsequent "slingshot" of the pulsars. But the point source in Cassiopeia A moves at 720,000 mph (1,188,000 km/h), and it's thought that perhaps as much as 15 percent of the neutron-star population is moving several times faster than this.

One possibility is that a small fraction of the energy of an asymmetric supernova provides a "kick" to the newborn neutron star. X-ray studies of the compact nebulae around the Crab and Vela pulsars reveal two-sided, asymmetric jets at positions that correspond to their lines of motion across the sky. Moreover, the observed jets also appear to be aligned with the rotation axis of each pulsar. Are they the vestiges of more powerful jets that accompanied the birth of the neutron stars?

New evidence for asymmetry comes from polarization studies of numerous supernovae by Lifan Wang, now at Lawrence Berkeley National Laboratory. Polarization of light occurs when light is scattered and oriented in a certain direction. When light scatters through the layers of the expanding shell of a supernova, it retains information about how it was scattered. If a supernova is spherically symmetric, all orientations of scattered light will be present equally, and the light will carry no net polarization. Wang found the light from more than a dozen supernovae is polarized, which implies that asymmetry is an inherent part of the supernova process. Not surprisingly, supernovae of type Ib/c tend to be the most highly polarized.

The growing polarization evidence, Wheeler says, means, "It's not that Cas A and '87A are a couple of oddballs, but that every single core-collapse explosion is asymmetric, without exception so far — so that's a new observational fact on the ground."



THE CRESCENT NEBULA (NGC 6888) in Cygnus is energized by WR 136, a Wolf-Rayet star at its center. The star loses the equivalent of our Sun's mass every 50,000 years thanks to a brisk stellar wind currently clocked at 4 million mph (6.3 million km/h). The wind has broken through a shell of slower-moving material ejected during the star's earlier red supergiant phase. T. A. RECTOR (NRAO/AUI/NSF)

The standard model for turning a core collapse into a supernova involves the emission of neutrinos after the core has compressed to nuclear density and rebounded, or "bounced," creating a neutron star. The total energy available in neutrinos is 300 times the energy of an ordinary supernova. And although less than 1 percent of neutrinos deposit their energy in the neutron star's dense atmosphere, the energy causes that layer to expand and convect. Woosley explains that astronomers think neutrinos blow up the supernova, but the computer models are not consistent. Sometimes they produce explosions, and sometimes they don't. In the few computer models that include rotation, a bipolar pattern naturally emerges at the core. It remains to be seen if this can account for the shapes of real supernovae as determined by polarimetry.

"The fact that we now know they're asymmetric — it's not a speculation, it's observational fact — and that the neutrinos alone haven't really done the job, invites me to think that whatever's making it asymmetric is also a new piece of physics," Wheeler says. "But I can't prove that yet. That's a long way down the pike." Computer simulations of core collapse are only beginning to include rotation, let alone magnetic fields. Wheeler argues that both are crucial to understanding core collapse and cites the discovery of magnetars — neutron stars with magnetic fields 1,000 times stronger than that of the Crab pulsar — as evidence.

He sees an opportunity for a collapsing star to make magnetic jets in the initial collapse phase when the neutron star is forming.

"Once you've got the neutron star formed, then it's going to be causing differential rotation," says Wheeler. That's prime territory for what Wheeler calls the magnetorotational instability, which builds up a magnetic field "like gangbusters" in the milliseconds following the core bounce. This creates what Wheeler calls the "toroidal jet," which moves out at about 10 percent the speed of light and has the potential to burrow all the way through the star. "If enough of its energy is trapped in the star, it could blow the whole star up," he says. "If it turns out to be a narrow jet that punches out like a needle through a loaf of bread, then you would not blow the star up or blow it up only weakly." In that case, the collapse continues, the neutron star becomes a black hole, and a third, high-velocity jet may form — a physical situation similar to that required for Stan Woosley's collapsar.

"We've got the bipolarity. We've got the asymmetry. We've got the fact that if it's rotating fast enough it will be magnetic, and we have a reservoir of energy. We also think a jet can blow up a star," Wheeler says. But there remains the big step of turning rotation and magnetic fields into a jet. "It's not a slam-dunk. It smells right to me," he quips, "but, you know, things have smelled right to me before in my career."

Gamma-ray bursts solved!

Astronomers finally understand the universe's most powerful explosions. /// BY STEVE NADIS

Since their discovery some 35 years ago by military satellites monitoring nuclear explosions, gamma-ray bursts (GRBs) have remained one of astronomy's great mysteries. They appear at seemingly random spots in the sky a few times a day, unleashing — for between a fraction of a second and about a minute — prodigious blasts of energy that, by some accounts, rival the Big Bang itself.

The origins of these bursts stumped researchers for decades, but the picture is now coming into sharper focus. A few years ago, scientists found that the burst energy is not sprayed in all directions. Instead, it's channeled into narrow, cone-shape beams, or jets. Even more recently, they found further evidence for scenarios that create both long- and short-duration GRBs.

Most of these jets pass by unseen, but, occasionally, one is pointed right at us. Far from feeling uneasy, astronomers who study gamma rays live for the chance to glimpse these high-energy photons.

Understanding the beamed nature of GRBs enables investigators to estimate, in one fell swoop, both the energy of bursts and their frequency. "If you didn't know the geometry, and assumed spherical emission when it's really conical, you could infer an energy release 1,000 times bigger than it really is," notes Shri Kulkarni of the California Institute of Technology. "And if the beams are as narrow as we think they are, for every GRB I see, there are 1,000 I don't see."

One of the most telling clues about the origin of GRBs was uncovered March 29, 2003, when NASA's High Energy and Transient Explorer (HETE-2) satellite detected a burst in the constellation Leo. The burst's subsequent "afterglow" revealed the GRB arose just 2.6 billion light-years away and was associated with a bright supernova that occurred around the same time. Today, theorists link the most common class of bursts (those lasting longer than 2 seconds) to the creation of black holes when stars at least 30 times the Sun's mass collapse and die in a blaze of supernova glory.

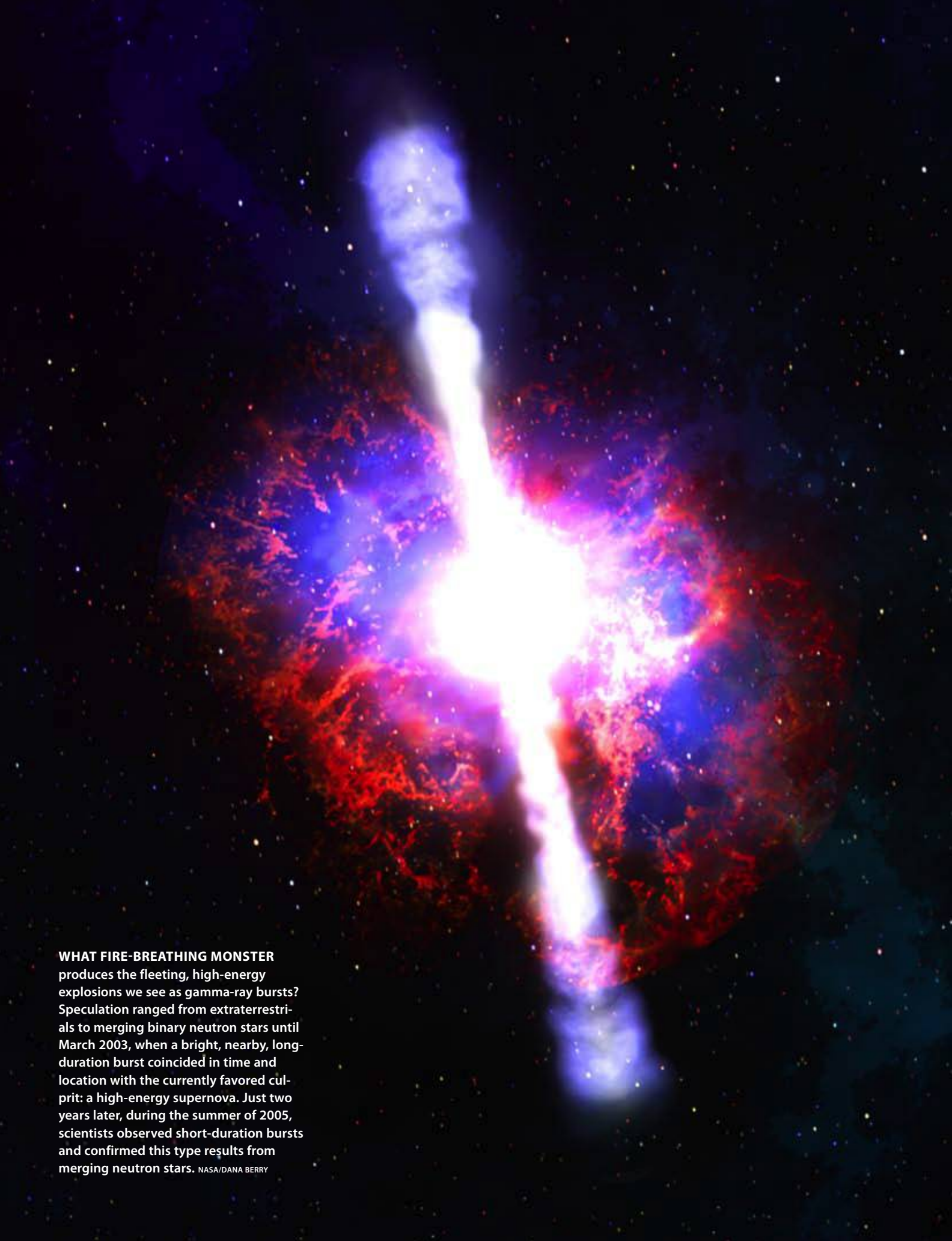
The suggestion that gamma rays are shot through space from a two-way cosmic cannon has been around for at least a decade, and nature offers other examples of jetted flows from stars and active galactic nuclei. But it is difficult to determine whether the gamma-ray pulses periodically detected by our orbiting instruments are beamed in jets or radiated in all directions.

This problem is compounded by special relativity. In the standard "fireball" model of GRBs, astrophysicists think gamma rays are produced from the extreme heat generated by internal collisions within a torrent of material ejected from a dying star at close to the speed of light. Photons emitted from a hot, high-velocity source don't wander all over the place. Instead, they concentrate in discrete, laser-like beams, traveling perpendicular to the dying star's surface. The faster the surface expands, the narrower the beam. One consequence of relativity, Kulkarni explains, is that "very fast-moving surfaces do not reveal themselves fully. You see only a small portion. And if you see only a little bit, you can't tell if it's an entire sphere or a small section of a sphere like a cone."

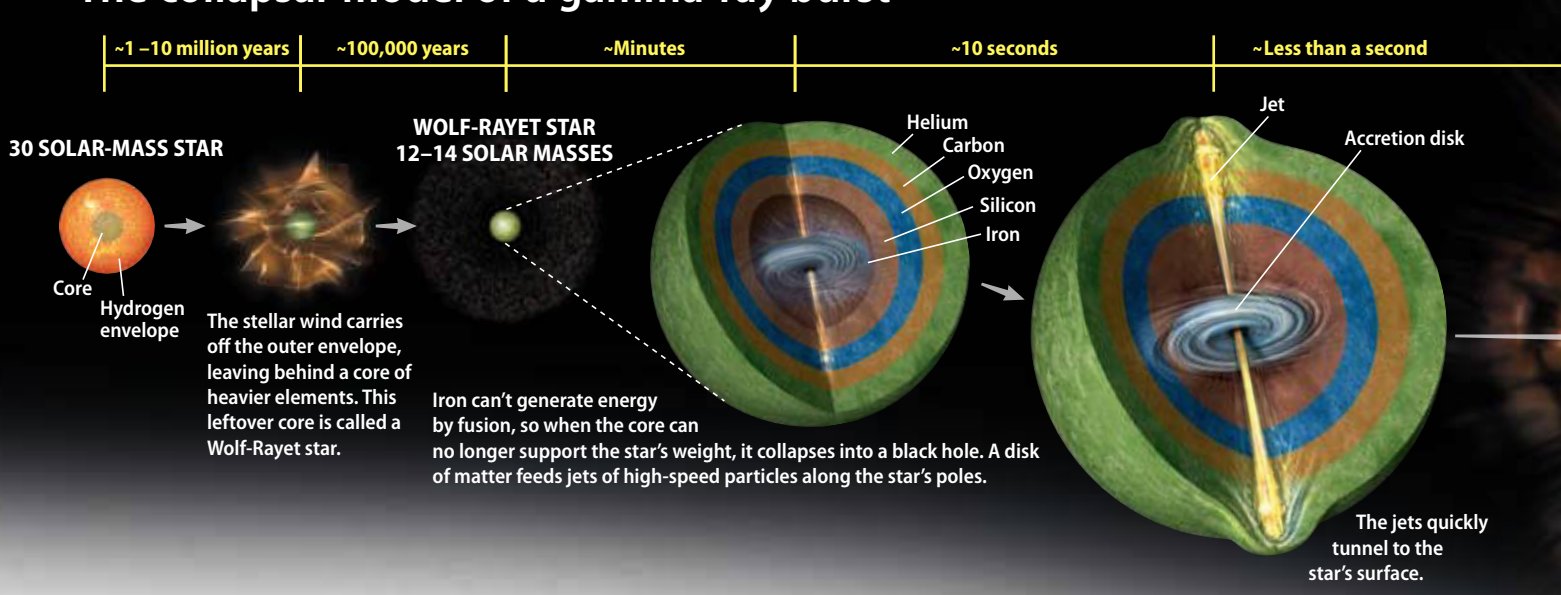
The first afterglow

The GRB model sharpened dramatically in 1997 with the discovery of GRB afterglows — X-ray, optical, and radio emissions that persist for weeks and months after bursts. Afterglows, according to the fireball model, occur when jets bump into the material the star shed earlier in its life.

Steve Nadis *is an* Astronomy *contributing editor. He lives in Cambridge, Massachusetts.*



WHAT FIRE-BREATHING MONSTER produces the fleeting, high-energy explosions we see as gamma-ray bursts? Speculation ranged from extraterrestrials to merging binary neutron stars until March 2003, when a bright, nearby, long-duration burst coincided in time and location with the currently favored culprit: a high-energy supernova. Just two years later, during the summer of 2005, scientists observed short-duration bursts and confirmed this type results from merging neutron stars. NASA/DANA BERRY


The collapsar model of a gamma-ray burst
~1 –10 million years
~100,000 years
~Minutes
~10 seconds
~Less than a second
30 SOLAR-MASS STAR
Core
Hydrogen envelope
WOLF-RAYET STAR
12–14 SOLAR MASSES
The stellar wind carries off the outer envelope, leaving behind a core of heavier elements. This leftover core is called a Wolf-Rayet star.
Helium
Carbon
Oxygen
Silicon
Iron
Iron can't generate energy by fusion, so when the core can no longer support the star's weight, it collapses into a black hole. A disk of matter feeds jets of high-speed particles along the star's poles.
Jet
Accretion disk
The jets quickly tunnel to the star's surface.

The jets slow down steadily during the afterglow phase. When the speed dips below a critical value, it becomes possible to see the jet's "edge." Because spheres, by definition, have no edges, viewing this "edge" was taken as proof the emission isn't spherical.

In 1997, James Rhoads, an astronomer at the Space Telescope Science Institute (STScI), encapsulated these ideas in a simple diagnostic test called the "jet break." After running into surrounding material, Rhoads said, a jet will lose speed and start to expand sideways. When this happens, the afterglow's luminosity falls off sharply as light focused into a narrow cone becomes more diluted. This should appear as a change in the slope of the "light curve" — a graph of luminosity versus time — at the precise point when brightness begins to decline more abruptly.

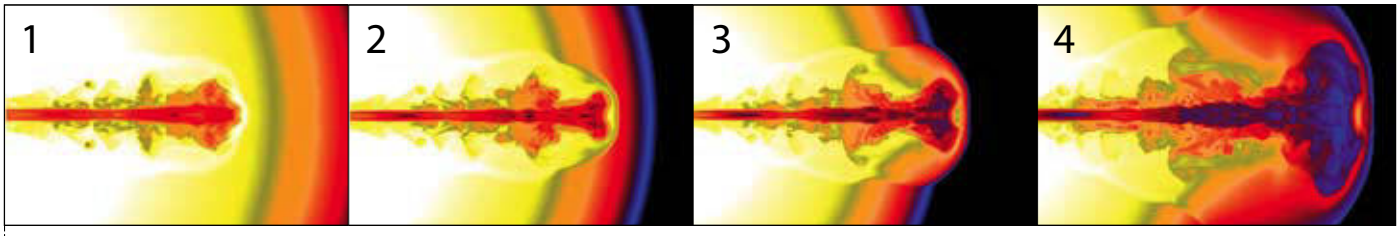
In a 1999 study, Re'em Sari of the California Institute of Technology and his colleagues found indications of "jet-like behavior" in three previously observed GRBs. Luminosity was dropping so quickly in those cases that the scientists concluded the afterglow observations must have begun after the jet break.

But scientists needed a larger observational sample to draw meaningful comparisons between bursts. In 2001, Dale Frail of the National Radio Observatory, along with Kulkarni, Sari, and 11 other astronomers, examined the light curves of 17 GRB afterglows in a variety of wavelengths. After confirming that jets focused the gamma-ray energy, the team calculated the jets' angular sizes based on when the jet breaks occurred. The longer the time between the blast and the jet break, the bigger the "opening angle" of the jet's cone. Most jets, they concluded, were just a few degrees wide. An independent analysis by Alin-Daniel Panaitescu of Princeton University (now at the University of Texas, Austin) and Pawan Kumar of the University of Texas, Austin, reached similar conclusions.

Clocking GRB energies

Knowledge of beaming angles is important because scientists now think different angles account for the different luminosities seen in gamma-ray bursts. Tightly focused jets look brighter than jets that are more widely dispersed. "Early on, people didn't realize how small the beams are," says Stan Woosley, a theorist at the University of California, Santa Cruz. "They assumed angles of about 20°, but now it looks closer to 4°."

Narrow beams mean that for every GRB we observe, there are 500 to 1,000 bursts invisible to us because they're pointing in another direction. Statistically, the data suggest that at least 1,500 GRBs occur each day, which is equivalent to a birth rate of one stellar-mass-size black hole each minute. This figure, says Woosley, means just "1 percent of the stars massive enough to die

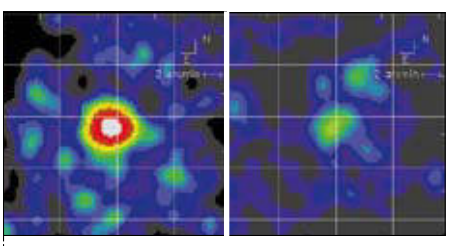


JETS OF RELATIVISTIC PARTICLES destined to become a gamma-ray burst force their way out of a massive star in this computer simulation. According to the leading theory, when a massive dying star can no longer support its own weight by nuclear fusion, its core collapses into a black hole surrounded by a spinning disk of material. Magnetic fields may accelerate the particles in this disk to near light-speed along the star's rotational axis. These jets tunnel through the star in about 10 seconds, and, along with a powerful wind of particles from the accretion disk, they destroy the star in an extremely energetic supernova. If the jets are aimed within about 5° of Earth, observers will detect the highest-energy particles (yellow and orange) as a gamma-ray burst that lasts for as long as it takes for the black hole to consume the star's inner core — longer than 2 seconds, and usually about 20 seconds. WEIQUN ZHANG/STAN WOOSLEY

as supernovae end up as GRBs."

Angular calculations also permit scientists to estimate the total gamma-ray energy release, which appears to be fairly constant from one burst to the next: roughly 10^{51} ergs. GRBs are like "standard bombs," just slightly more energetic than supernovae, according to Woosley. They retain the title of "nature's grandest explosions" by a slim margin, but they are easily "the brightest explosions since the Big Bang."

Without taking beaming into account, GRBs seemed impossibly energetic. They appeared to release 1,000 times more energy — and theorists had little luck concocting workable scenarios. The lower, revised estimate fits well with models that equate GRBs with typical supernovae.



THE FIRST X-RAY AFTERGLOW (left) was detected by the satellite BeppoSAX 8 hours after a GRB was observed from the same location February 28, 1997, and again after 3 days (right). Afterglows help pin down GRB distances and host galaxies.

ENRICO COSTA/BEPPOSAX TEAM

Death throes

Jet flows are an integral feature of the so-called collapsar model developed by Woosley and collaborators. In this model, arguably the leading one for long GRBs, the GRB and supernova happen at the same time and are powered by the same energy source: the terminal collapse of a massive star. The collapse at the center of the star creates a black hole surrounded by a spinning disk of matter. The rotating black hole and disk wind up magnetic fields, which funnel particles from the disk into jets along the star's rotation axis. A powerful wind blowing from the disk, along with the jets, rip the star apart. Relativistic jets blast out of the star in opposite directions and create gamma-ray emissions. The star's outer shell expands at a more modest pace

~20 seconds

~Minutes to days

SUPERNOVA

Black hole

Shell

The jets and wind from the accretion disk blow the star apart.

Jet

Internal shocks

Gamma rays

The gamma rays we see in a burst actually are produced when relativistic particles run into each other about 10^{14} cm away from the star.

External shocks

Like a snow shovel that gets harder to push the more snow it picks up, the jets lose energy as they plow into interstellar matter. By the time the jets travel between 10^{16} and 10^{18} cm, these "external" shocks produce lower-energy (X-ray, optical, and radio) afterglows that can last from minutes to months.

Gamma rays

X rays

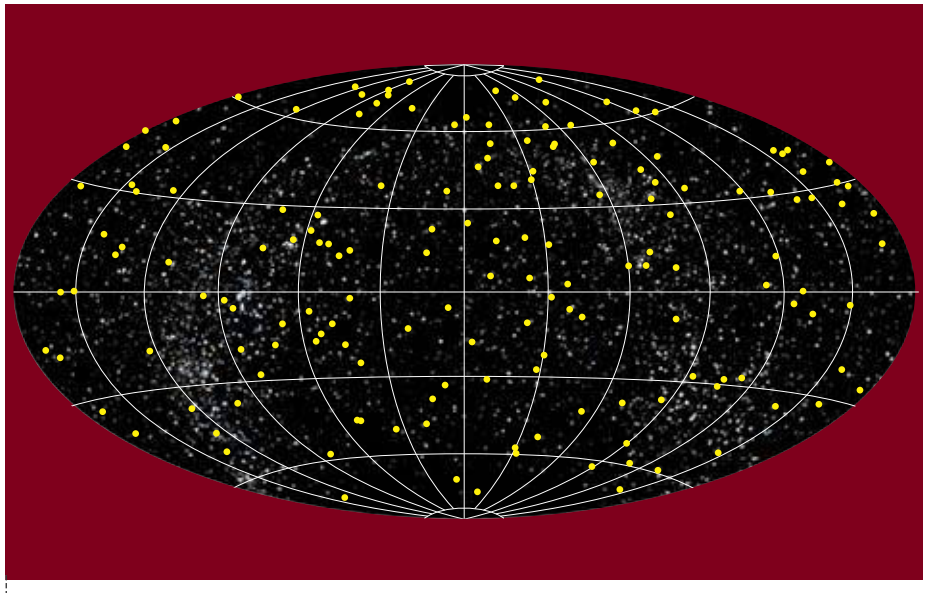
Optical

Radio

~ is a symbol that stands for "approximately"

ASTRONOMY: ROEN KELLY

NASA'S SWIFT SATELLITE, which launched in November 2004, is "swiftly" locating gamma-rays bursts (GRBs). The satellite has detected more than140 GRBs and imaged more than a quarter of their afterglows using onboard optical, ultraviolet, and X-ray telescopes. NASA/SPECTRUM ASTRO



THE GAMMA-RAY BURSTS (yellow circles) Swift detected in its first 18 months occur all over the sky. The blasts are the signatures of high-energy events: supernovae, neutron-star mergers, or black holes devouring neutron stars. NASA/SWIFT/DAVID SEAL/*ASTRONOMY*: ROEN KELLY

— the same amount of energy goes into moving a greater bulk of matter.

Although GRBs and supernovae usually are considered separate phenomena, in this model, they're different manifestations of the same explosion. These events are rare. Perhaps 1 percent of supernovae are associated with GRBs. Scientists think the rest are powered by neutron-star formation and neutrinos.

Additional support for the link between GRBs and supernovae comes from observations that show bursts tend to originate in star-forming regions. "In places where lots of stars are born, a lot of massive stars will also be dying," notes theorist Tsvi Piran of Hebrew University in Israel.

Andrew Fruchter, an STScI astronomer, agrees. "The hosts show signs of being unusually star-forming: They are blue and have strong emission lines," he says. "They also show disturbed morphologies."

Other suggestive evidence comes from a 2002 study of the X-ray afterglow of GRB011211 using the XMM-Newton space telescope. James Reeves of NASA and his colleagues conducted a detailed spectral analysis of the afterglow. They found light chemical elements like magnesium, silicon, sulfur, argon, and calcium — all elements typically flung into space by a supernova.

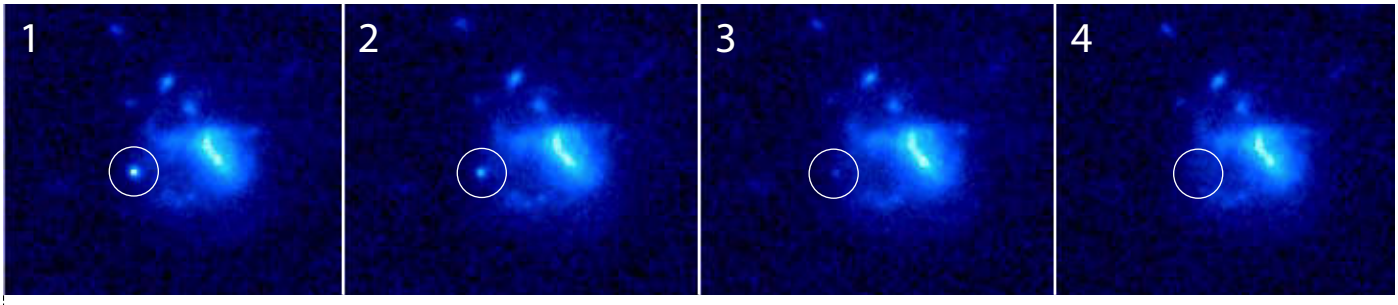
With the various pieces of evidence combined, Woosley believes the case tying GRBs to star death is compelling. "We have a working model, and there's even some consensus in the community, but that doesn't make it right," he says.

He points out that a dozen years ago, many people believed gamma rays came from the rapid accretion of matter onto a neutron star. Although the idea makes sense, it is absolutely wrong, Woosley says. "I should know because it was my model."

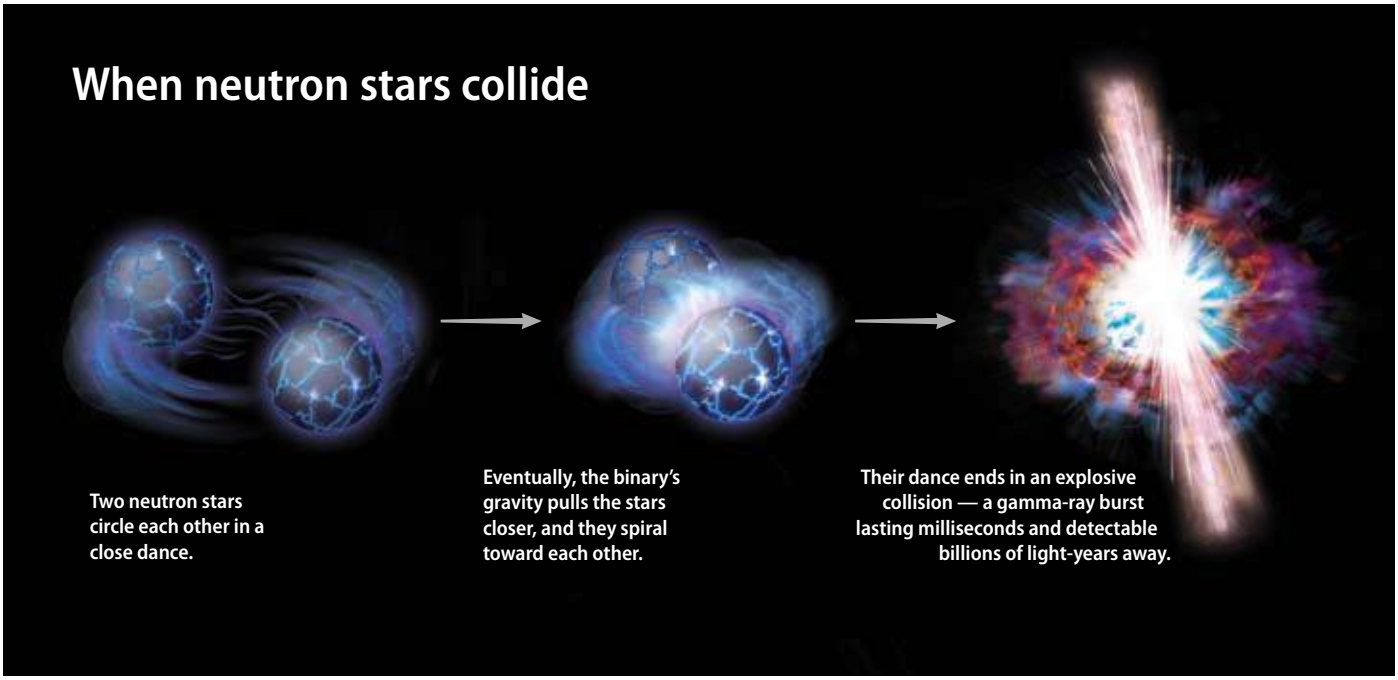
Uncertainties afflict most aspects of the currently favored collapsar model. "Even if we know the GRB is caused by the explosion of a massive star, that still doesn't tell us how it blew up," Woosley says. On the most basic level, researchers can neither describe how jets are made, nor what they are made of, although it is often assumed they consist of the universe's most abundant material, hydrogen.

Fundamental questions remain about the enigmatic jet source that accelerates matter to relativistic velocities and tightly focuses the beams. "What is the mysterious engine that produces so much energy, yet can operate with such fine precision?" asks Kulkarni. "It's a rare combination of the delicate and the powerful." He is particularly intrigued by the focusing mechanism. "Making a cone of just 1° is like cutting a pizza into 360 slices. How does nature make these incredible pizzas?"

Kumar is mystified by the apparent "constancy of energy" among bursts, which he believes must be an important clue to the explosion's cause. "Why isn't there a bigger variation in energy, and why are you only



THE HUBBLE SPACE TELESCOPE (HST) and many ground-based telescopes detected an optical source at the same location as the May 9, 2005, gamma-ray burst. This was the first time astronomers observed a short GRB's afterglow in visible light. These images, which HST took 5.6, 9.8, 18.6, and 34.7 days after the burst, show the fading afterglow. DEREK FOX/PENNSYLVANIA STATE UNIVERSITY


When neutron stars collide
Two neutron stars circle each other in a close dance.
Eventually, the binary's gravity pulls the stars closer, and they spiral toward each other.
Their dance ends in an explosive collision — a gamma-ray burst lasting milliseconds and detectable billions of light-years away.

ASTRONOMY: KELLIE JAEGER

tapping about 1 percent of the total?" he asks. "It's as if you had $100,000 in a group bank account and everybody can only take out $1,000. There has to be a reason. Otherwise, people might take out $10, $100, or $10,000."

Kumar also is trying to understand the properties of jets in a more precise way. "In our models, we think in terms of a cone carved out of a sphere, but things may not be as neat as a uniform cone," he says. "Different parts of the jets could be propagating at different speeds."

The GRB future is bright

With all the unanswered questions still swirling around bursts and jets, astrophysicists have pinned high hopes on NASA's Swift mission, which was launched November 20, 2004. The mission is aptly named: Once gamma radiation hits Swift's Burst Alert Telescope, the satellite slews (usually within a minute) to observe the likely GRB in optical, ultraviolet, and X-ray radiation.

As of August 2006, the spacecraft has spotted about 140 GRBs. Swift has also observed the afterglows of almost half of those GRBs well enough to determine their locations. This greatly increases the number of bursts with known locations.

Mission members wear pagers that go off whenever the satellite detects a burst. Burst positions are "given to people on Earth within seconds rather than hours, so we can look at the afterglows very quickly," says Sari. "That means we can catch jets with the smallest angles and earliest breaks."

Meanwhile, some astronomers pursue an independent strategy, one based on another test Rhoads proposed in 1997. If GRBs broadcast in discrete beams, then we should be able to see afterglows in some cases where it is impossible to see the bursts themselves. These "orphan afterglows," as Rhoads calls them, will be hard to find because they're much fainter and rarer than supernovae. "But they have to exist if this picture is right," he says.

A GAMMA-RAY BURST'S jet source is "a rare combination of the delicate and the powerful." — *Shri Kulkarni*

Even without an orphan-afterglow sighting, it appears that after 35 years of detective work, researchers are finally getting to the bottom of the gamma-ray burst mystery — for both long-duration and short-duration bursts.

Another definition

In the last year, researchers have pinned down the likely cause of short-duration bursts — those lasting less than 2 seconds. Short bursts require a different mechanism — the merger of two neutron stars or a neutron star and black hole. Scientists had suspected this scenario as the source of some GRBs for years but lacked direct evidence. Because short bursts are quite brief — usually lasting just tens of milliseconds — telescopes and satellites could not move quickly enough to pinpoint the GRB's location.

During summer 2005, both Swift and HETE-2 observed three short bursts well enough to determine their locations. Other space-based and Earth-based telescopes observed the afterglows in a range of frequencies. By analyzing the afterglows, scientists found the short GRBs lie between 2 and 3 billion light-years away — closer than long GRBs. All three short bursts lay on the outskirts of their host galaxies, "just where old merging binaries are expected," says George Ricker, HETE-2's principal investigator.

Observations over the next few years with Swift, HETE-2, and soon the Gamma-ray Large Area Space Telescope (GLAST), scheduled for an August 2007 launch, should settle the origin of GRBs once and for all.

GRBs aren't the only gamma-ray sources. Swift records other signals, a broad range of "optical transients," emanating from supernovae, novae, flare stars, and active galactic nuclei. In addition, says Woosley, "There are likely to be forms of gamma-ray transients we don't know anything about."

So, gamma-ray sleuths won't be going out of business anytime soon. Just as one GRB mystery is solved, other questions draw our attention back to these errant high-energy jets from the far reaches of the cosmos.

DARKER than the night

Astronomers are scrambling to figure out galaxies that nearly disappear into the night sky. Yet, these oddballs could outnumber normal galaxies ten to one. /// BY BRUCE DORMINEY

Even on the clearest, darkest night, bright galaxies appear as fuzzy little blobs through the best binoculars. Those fortunate enough to have exceptional naked-eye night vision sometimes can distinguish the luminous glow of the Andromeda Galaxy (M31), our nearest spiral neighbor. But big galaxies like Andromeda and the Milky Way make up only a tiny part of our own Local Group of galaxies and, indeed, of the cosmos as a whole.

At the limits of our technological prowess in the radio and optical spectra lies a bizarre universe of galaxies that defy theoretical explanation. Some of these oddballs have surface brightnesses 6 magnitudes (250 times) fainter than the background of the night sky. (Surface brightness measures how bright a given area of an object appears.)

Although low-surface-brightness (LSB) galaxies have been surveyed and studied for the past 2 decades, they still challenge almost everything astronomers know about galaxy formation, galactic dynamics, and gravitation.

By definition, any diffuse galaxy with a surface brightness about one magnitude fainter than the night-sky background qualifies as an LSB galaxy. Since their discovery in the mid-1980s, more than 3,000 of these objects have been detected and cataloged. They range in size from a small fraction of the Milky Way up to some 10 times the dimensions of our galaxy.

Malin 1, a spiral monster lying behind the Virgo cluster some 1.1 billion light-years from Earth, remains the largest LSB galaxy detected. And although most LSB galaxies are dwarf irregulars, at least several dozen giant LSB spirals approach the size of Malin 1. Astronomers have likened LSB galaxies to the

LOW-SURFACE-BRIGHTNESS GALAXIES typically don't look like much, even when they're nearby. The Sagittarius Dwarf Irregular Galaxy (right) epitomizes their ephemeral demeanor.
NASA/ESA/Y. MOMANY (UNIVERSITY OF PADUA)

ESO

NOAO/NSF/AURA

SUBARU TELESCOPE, NAOJ

NOAO/NSF/AURA

MORE THAN 80 PERCENT of Local Group galaxies qualify as low-surface-brightness dwarf galaxies. The examples shown on this and the following page show these galaxies range from bits of near-nothingness to entities that are slightly more substantial.

vanishing Cheshire cat from *Alice's Adventures in Wonderland* because often the only detectable part is the fleeting "grin" from their cores. Their outer regions are as difficult to image as the netherworlds at the fringe of our solar system.

Because most LSB galaxies appear to be young and full of hot, blue stars, they are best observed with wide-field telescopes with detectors sensitive to the blue part of the optical spectrum. Follow-up observations by radio telescopes traditionally involve detecting the telltale emission of neutral atomic hydrogen at a wavelength of 21 centimeters. However, this is time-consuming and allows astronomers a limited view of what's happening in any given LSB galaxy.

It's no wonder that as late as the 1970s, astronomers were influenced by "selection bias" in how they detected and recorded galaxies' central surface brightnesses. (Distant galaxies with low surface brightnesses tend to melt into the background, while those with high surface brightnesses appear like stars. This caused astronomers to miss a lot of galaxies.) So when Ken Freeman, an Australian astronomer, wrote a 1970 paper on the correlation between a galaxy's observed central surface brightness and its rate of detection, others ran with the idea. His paper spawned "Freeman's Law," with the axiom that most spiral galaxies appear to have a central surface brightness of about 21.6 magnitudes per square arcsecond.

But in the late 1970s, while measuring the brightnesses of some 20 galaxies culled from the Palomar Observatory Sky Survey, doctoral candidate William Romanishin found spiral galaxies 1.5 to 2 times fainter than what was considered normal. Romanishin, now an astronomer at the University of Oklahoma, had opened the door to the possibility that astronomers had been observationally blindsided by high-surface-brightness objects.

On the trail of Malin 1

By the mid-1980s, David Malin, an astronomer and astrophotographer at the Anglo-Australian Observatory in Siding Spring, Australia, was surveying galaxies in the Virgo cluster, the nearest rich cluster of galaxies, when he discovered Malin 1. He was using the 1.2-meter wide-field UK Schmidt telescope and a photographic technique that came to be called "Malinization."

The technique involves making a copy of the original glass plate using high-contrast film and a diffuse light source, not unlike an X-ray viewbox in a doctor's office. These Malinized films then can be added together photographically to obtain a deeper and more contrasty image. Although CCDs are more efficient than photographic plates, photography still proves useful for detecting large low-surface-brightness objects.

"Photography has all sorts of irritating problems," says Malin, "but for detecting faint things against the night sky, it's bloody good. So if you see some sort of faint blob there, particularly on more than one picture, then it's real. I came across this rather strange galaxy that had a big, fuzzy nucleus and some clumpy stuff in its outer envelope."

He sent his data to University of Oregon astronomer Greg Bothun, who, at the time, was working on the detection of LSB galaxies with Chris Impey, now an astronomer at the University of Arizona. Bothun remembers using the Arecibo radio telescope in

Puerto Rico to look for the 21cm signature of neutral hydrogen from Malin's odd-looking galaxy.

He picked up the hydrogen emission and found it to be significantly redshifted thanks to the universe's expansion. Malin 1 was receding from Earth at 15,500 miles per second (25,000 kilometers per second), which implied it was much farther away than astronomers had expected. If the distance derived from the velocity was accurate, Malin had stumbled upon a galaxy that, from all appearances, had just begun the business of star formation. Yet, incredibly, this galaxy had a surface brightness of only about 28 magnitudes per square arcsecond.

Astronomers estimate that Malin 1, which is characterized by a large galactic bulge and an active nucleus, is only 3 to 5 billion years old. Thus far, no supernova has been detected in Malin 1 or any of its LSB counterparts.

In normal galaxies, supernovae create the heavier elements that, in turn, help cool the molecular gas that collapses to form stars. Eventually, high-density molecular clouds reach a point where they become gravitationally unstable and start to fragment and form stars. But because LSB galaxies appear to be supernova-free, they contain few heavy elements. So, LSB galaxies like Malin 1 are short on both high-density molecular clouds and busy star-forming regions.

Galaxies full of gas

Although some astronomers dispute the apparent youth of LSB galaxies, as a rule, most of these objects tend to have lots of young, blue stars and hydrogen gas. They also appear to evolve at a much slower rate than higher-density, higher-surface-brightness galaxies like the Milky Way.

By comparison, while the Milky Way already has converted some 90 percent of its gas into stars, LSB galaxies still are sitting on the majority of their neutral hydrogen reserves. It's this neutral hydrogen that radio astronomers observe as a large, extended, low-surface-brightness disk attached to a brighter, central core.

In some cases, 90 percent of an LSB galaxy's gas has yet to be converted into stars. But even though some LSB galaxies have a total gas density less than the theoretical value needed for star formation, they clearly are forming stars.

"Take our Milky Way Galaxy and increase its radius by a factor of 3 while keeping the same number of stars in it," says Bothun, "and you would have a low-surface-brightness galaxy. Star formation shouldn't occur in low-density environments, but we have entire galaxies that have low-density environments brimming with stars. They may become higher-surface-brightness spiral galaxies in the future, but it might take another 5 billion years."

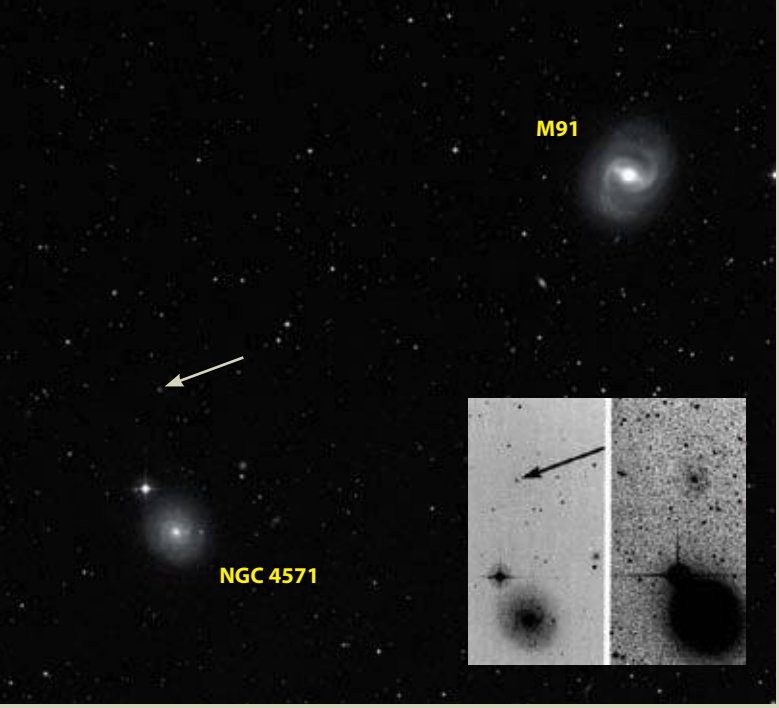
How could such objects form? Galaxies with normal surface brightnesses appear to form through a "bottom-up" scenario in which dwarf galaxies — fueled by a large amount of dark matter in their galactic halos and central cores — continually merge to form larger structures. Recent observations with the Hubble Space Telescope suggest the bulk of the universe's galaxies sprouted this way within the first 6 billion years of the universe's existence.

The unseen dark matter gravitationally attracts neutral hydrogen into a budding galaxy's dense core, causing the whole galaxy structure to spin up due to angular momentum. But just why LSB disks collapse into something 3 to 5 times larger than our own galaxy remains hard to explain.

NOAO/NSF/AURA
NGC 6822

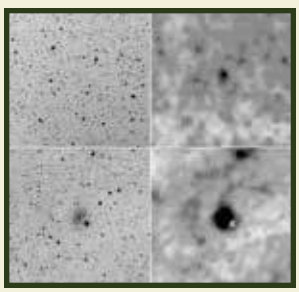
NOAO/NSF/AURA
SEXTANS B

NOAO/NSF/AURA
IC 10



LSB GALAXY MALIN 1 (arrow) **is the largest known. It lies well beyond the Virgo cluster and barely appears in this image from the Palomar Observatory Sky Survey. Note the much brighter galaxies NGC 4571 (below Malin 1) and M91 (upper right). Malin 1 barely appears even in an enhanced image (inset). The object, whose surface brightness falls well below that of the night sky, glows dimly north of NGC 4571.** DIGITIZED SKY SURVEY

TEASING SUBSTANCE OUT OF NEAR-NOTHINGNESS



TWO LOCAL group galaxies, Andromeda V (top two images) and Andromeda VI (bottom two), appear weakly in the original Palomar Observatory Sky Survey images (at left in each pair). The galaxies show up more clearly once the images are enhanced (at right in each pair). DIGITIZED SKY SURVEY

According to Newtonian physics, as the radius gets bigger, the rotation velocity of an LSB galaxy should slow. But that's not what astronomers observe. Thus, one explanation for the unexpectedly high velocities found in LSB spirals is that the gravitational influence of hidden dark matter provides these galaxies with a little extra angular momentum.

But even if dark matter spins up these LSB galaxies, at some point, Bothun says, they should become so diffuse they would no longer hold together. The ratio of dark matter to ordinary (baryonic) matter would have to be some 10,000 to one — a configuration he says doesn't exist. He notes the Milky Way tips the scale at 90-percent dark matter to 10-percent baryonic, while Malin 1 is roughly 98-percent dark matter and only 2-percent baryonic.

"We don't really know why galaxies don't fall apart," says Mike Disney, an astrophysicist at Cardiff University in the United Kingdom. He first predicted the existence of diffuse, low-contrast, LSB-like galaxies in 1976. "Until we either find out what dark matter may be made of or map it more clearly than we can now," he adds, "it's just an ad hoc device that's been brought in to fix up a couple of observations."

Yet Stacy McGaugh, an astronomer at the University of Maryland with a longtime interest in galaxy dynamics, says his own optical observations bear out the fact that dark matter and luminous matter are "intimately coupled." However, McGaugh readily acknowledges he doesn't understand how or why dark matter and luminous matter appear to interact so closely if dark matter remains immune to electromagnetic interactions and is influenced solely by gravity.

Stanford University particle physicist Savas Dimopoulos believes dark matter actually may be ordinary matter from a parallel universe or universes gravitationally intertwined with our own. This would explain why dark matter appears to interact only with gravity and may be one reason gravity is a perplexingly weak force in comparison with electromagnetism. "If this dark matter is baryonic, then gravity would leak between two universes, and we would definitely be able to detect that with LISA," says Dimopoulos.

LISA, the Laser Interferometer Space Antenna, is a joint mission of NASA and the European Space Agency. In theory, it will be sensitive to gravitational radiation from dark matter in such parallel universes; however, its scheduled 2011 launch is delayed until at least 2013 due to NASA budget cutbacks.

On the trail of dark dwarfs

Meanwhile, numerical simulations predict that if our universe is dominated by cold dark matter — so large spiral galaxies form in a bottom-up scenario — then some 500 dark-matter-dominated dwarf galaxies should be left over from the Local Group's formation. Thus far, despite extensive surveys in visible light and radio waves, astronomers have detected only about 35 dwarf galaxies. Are the simulations missing something basic and predicting objects that aren't really there, or are hundreds of dark-matter satellites lurking out there in the Local Group that we just haven't been able to detect?

Josh Simon hopes he has found the first of these missing dwarf galaxies. After analyzing 21cm observations taken at Arecibo, Puerto Rico, Simon, a Robert A. Millikan postdoctoral scholar in astronomy at the California Institute of Technology in Pasadena, believes he and his colleagues at the University of California, Berkeley, may have found the first dwarf dark galaxy. While LSB galaxies always have stars in them, a dark galaxy is a theoretical object made of gas and dark matter but void of stars. And according to theory, astronomers expect most dark galaxies to be dwarfs.

Simon's candidate dark galaxy is a high-velocity cloud (HVC), an object consisting of neutral hydrogen gas and dark matter traveling so fast it seems unlikely to be bound gravitationally to our galaxy. Termed HVC 127–41–330 (the numbers denote its galactic longitude, latitude, and velocity toward the Sun), it measures some 20,000 light-years in diameter and lies some 2.3 million light-years from the Milky Way, between the Andromeda Galaxy and another Local Group spiral, M33.

It's the first HVC clearly not associated with the Milky Way itself. Simon believes this high-velocity cloud is a small, pristine

Bruce Dorminey *is an award-winning science journalist based in France. His book,* Distant Wanderers: The Search for Planets Beyond the Solar System, *is published by Springer-Verlag (2002).*

dwarf galaxy with an exceedingly low density that was left over from the Local Group's formation.

In the Local Group, hundreds of HVCs superficially look like this one. But this double-lobed, oval object is the only one astronomers have observed rotating. This rotation allowed Simon to measure the object's mass. He found it contains more than 4 times as much mass as its observed neutral hydrogen can account for, implying dark matter dominates the cloud. Simon hopes to observe this HVC with a 4m optical telescope to confirm it contains no stars, but he acknowledges, "It's difficult to understand how these things could have been sitting out there for billions of years without ever forming stars."

There even may be some subset of dark galaxies containing what Disney terms "frozen" disks. Such galaxies would have a disk of hydrogen held together by dark matter that, for some reason, had not formed stars. If all the galaxy's neutral hydrogen had fallen into its lowest energy state, then it couldn't emit 21cm radiation, and it would be nearly impossible to detect. But Disney believes there may be another way to detect such frozen galaxies: Their spectral fingerprints might show up as foreground noise in spectra of distant quasars — quasi-stellar, high-energy objects with large redshifts and high brightnesses.

"This inert hydrogen is capable of absorbing radiation from a background quasar," says Disney. "So you'll see a little nick in its spectrum. We find that when we look at quasars, they contain about 200 times as many nicks in them as we can explain as a result of ordinary galaxies standing between us and the quasars."

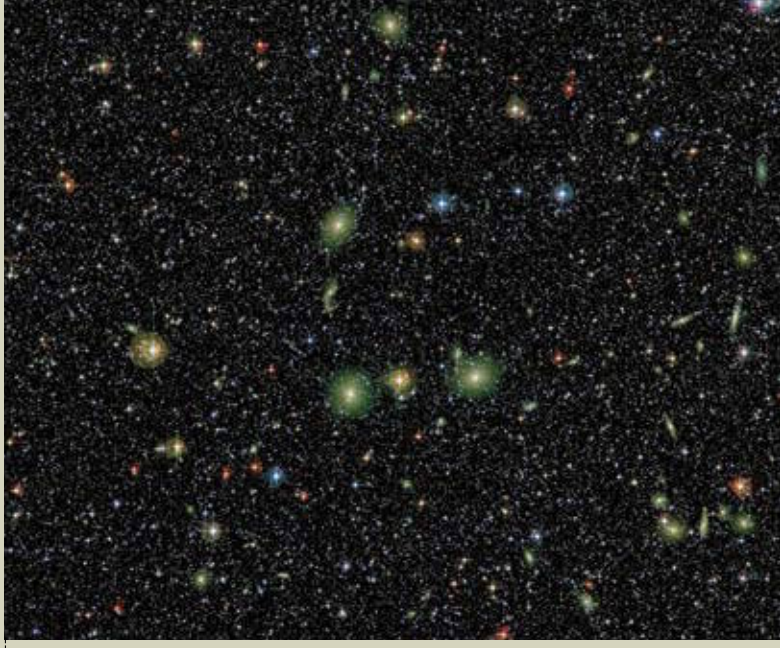
Even so, the future of detecting LSB galaxies lies in wide-field telescopes like the European Southern Observatory's 2.5m VLT Survey Telescope and 4m Visible and Infrared Survey Telescope for Astronomy. Both will sit atop Cerro Paranal in Chile's Atacama Desert, near the current site of the Very Large Telescope. Due to see first light in 2006 and 2007, respectively, both instruments will help shed light on Bothun's gut-level hunch that LSB galaxies could make up 90 percent of the galaxies in the universe.

Then, by the end of 2012, a consortium of institutions that includes the National Optical Astronomy Observatories, the University of Arizona, and the University of Washington, hopes to see operation of the $120-million Large-aperture Synoptic Survey Telescope (LSST). An 8.4m wide-field telescope, it will be capable of imaging almost the whole sky in 3 nights.

"The LSST will marry large aperture and wide field in an unprecedented way," says LSST Systems Scientist Chris Stubbs, an astronomer at the Harvard-Smithsonian Center for Astrophysics. In half the time of the Sloan Digital Sky Survey, the LSST will image objects 5 times fainter, covering the sky every few days either to look at what's changed or to build a deep composite image of a single LSB galaxy.

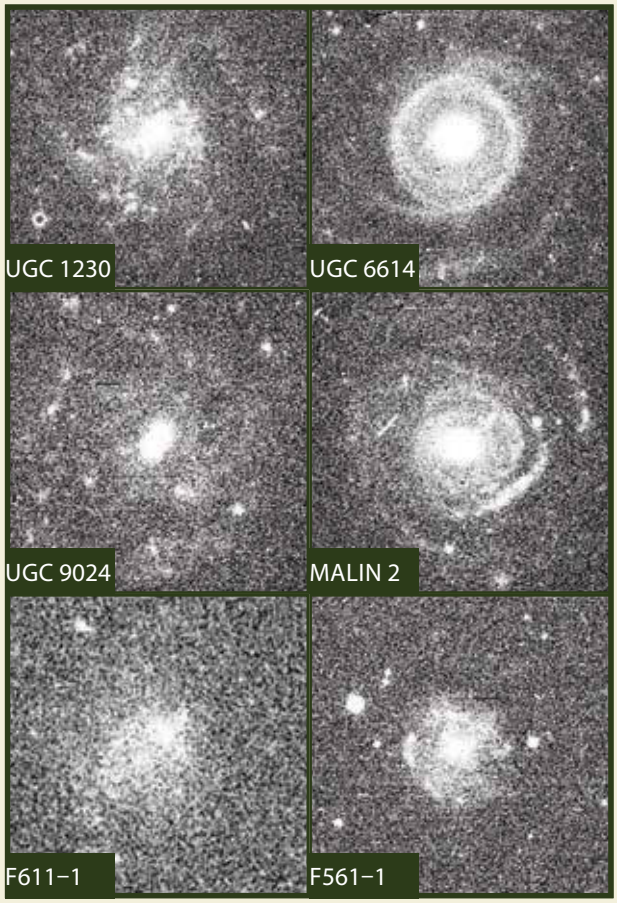
Ultimately, such new technology may allow astronomers to map the low-density local universe in greater detail than ever before. As observations with NASA's Chandra X-ray Observatory have recently pointed out, rivers of unfathomably hot gas trace an intergalactic web of dark matter within the Local Group of galaxies. It's part of a low-density cosmic web that appears to run along extended dark-matter filaments within clusters and superclusters of galaxies.

Astronomers hope future observations will enable them to differentiate and characterize LSB galaxies and their connection to the low-density fabric of the cosmic web itself.



MASSIVE GALAXY CLUSTER ACO 3627 lies 250 million light-years from Earth. Hundreds of high-surface-brightness galaxies can be seen in the cluster, but most low-surface-brightness galaxies would be invisible at this enormous distance. ESO

LSB GALAXIES IN THE DISTANT UNIVERSE



ALL IMAGES: GREG BOTHUN (UNIVERSITY OF OREGON)

LSB GALAXIES comprise perhaps 90 percent of galaxies in the cosmos, although astronomers have found only around 3,000 so far. The above sampling of galaxies shows they come in both spiral and elliptical shapes.

Searching for

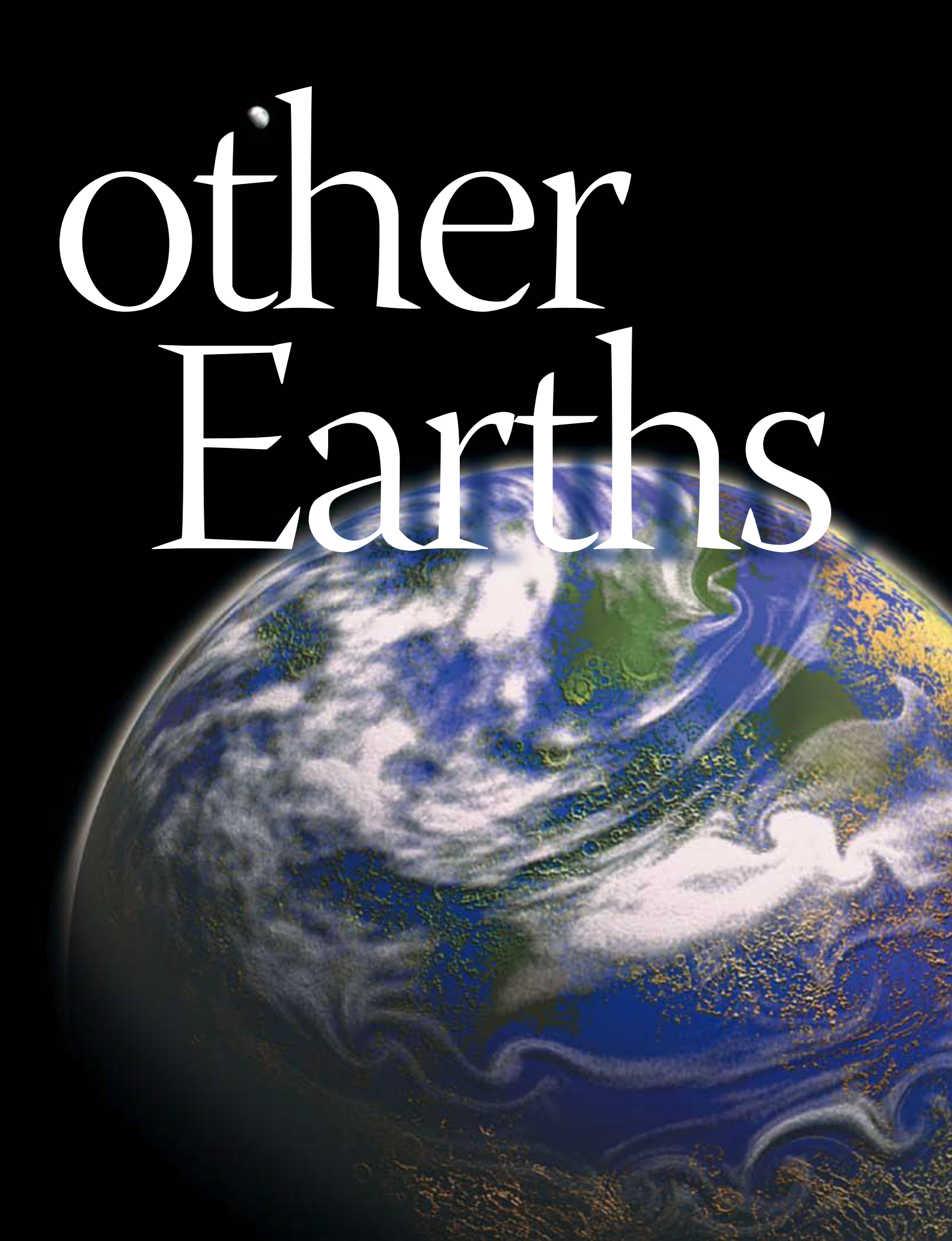
Scientists think we may be only a decade away from finding planets like ours in other star systems — and perhaps even detecting signs of life. /// BY RAY JAYAWARDHANA

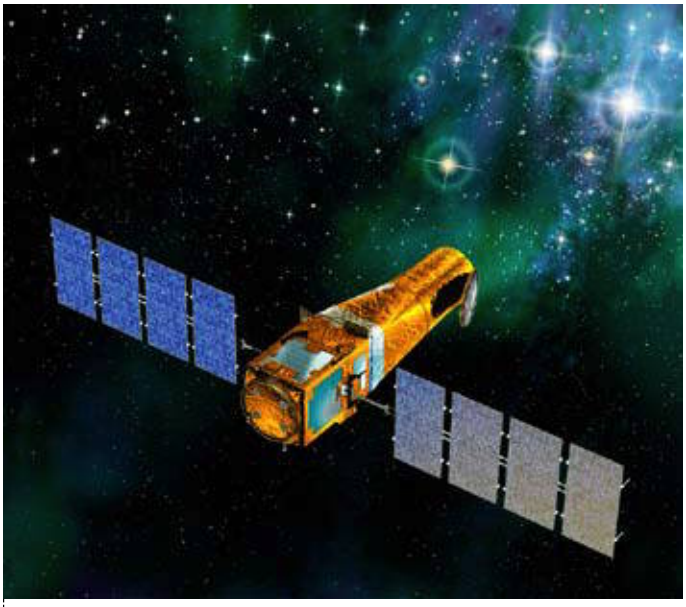
As the Galileo spacecraft flew past our planet in 1990 for a little gravitational kick on its way to Jupiter, it attempted to answer an intriguing question: Is there life on Earth? Carl Sagan, who persuaded NASA to train Galileo's instruments on our own "pale blue dot," didn't intend this as a tongue-in-cheek question. For him, it was a serious scientific query, with far-reaching implications. He wanted to investigate whether signs of life on Earth can be detected unambiguously from afar. ◖ Sagan's quest has gained renewed interest and urgency with the discovery of planetary systems around more than 160 nearby stars and improved prospects of searching for alien life. To be sure, most of the exoplanets found to date — discovered through their gravitational tugs on the parent star, by the dimming of starlight as they pass in front of it, or by magnifying light from a background star — are probably gas giants like Jupiter and Saturn. They are unlikely to harbor life as we know it. But some of these alien Jupiters might be accompanied by lower-mass brethren, perhaps even distant counterparts to Earth. A repeated dip in a star's brightness by a mere one part in ten-thousand could signal one's presence. Two satellite observatories — the French-led COROT mission (scheduled for launch in late 2006) and NASA's Kepler mission (scheduled for a 2008 launch) will look for just that signature of earthlike planets around 100,000 stars in our neighborhood.

OUR PALE BLUE DOT, EARTH, showed signs of life when the Galileo spacecraft flew by in 1990. The test proved we can detect life from afar. NASA/JPL

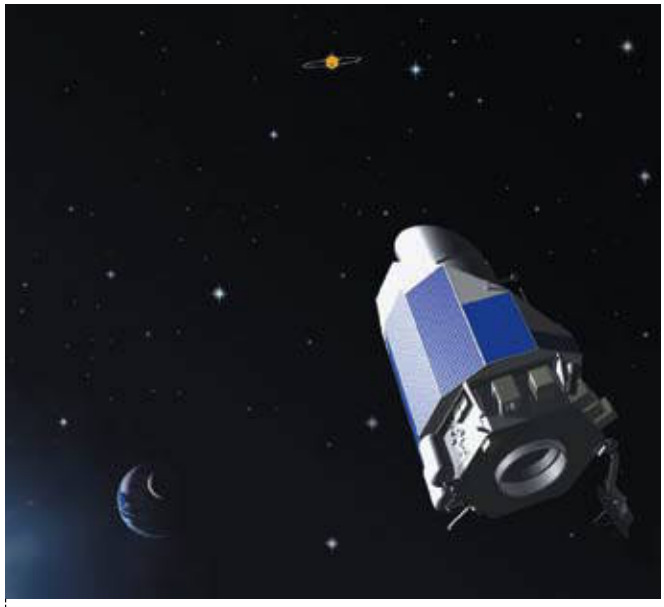
EXOTIC EARTHLIKE PLANETS may be common throughout the galaxy. Astronomers think they might find evidence of such planets, and maybe extraterrestrial life, within the next decade. *ASTRONOMY:* TOM FORD

other Earths





THE COROT SPACECRAFT will seek planets by looking for a dip in brightness caused by a planet passing in front of its parent star. CNES



NASA'S KEPLER MISSION will hunt for earthlike planets using the same technique employed by COROT. NASA

Finding an Earth-size planet is one thing, but detecting signs of life is quite another. Beyond Kepler and COROT, both NASA and the European Space Agency (ESA) plan to follow up with more ambitious space-borne observatories. Next up will be NASA's SIM PlanetQuest, tentatively scheduled for launch in 2015. After that, NASA's Terrestrial Planet Finder (TPF) and ESA's Darwin are designed to take pictures of an extrasolar Earth. More importantly, both TPF and Darwin are expected to break down the planet's feeble light into a spectral rainbow of colors to look for signs of life in its midst. The builders of these missions hope to achieve this remarkable feat by canceling the blinding glare of the planet's parent star. They'll do this either by combining observations from multiple telescopes in an array or by blocking the star with a cleverly designed opaque mask embedded within the optical system.

> "ANY ADVANCED CIVILIZATION that cared to inquire would know that life has been present on Earth for a very long time." — *Neville Woolf*

Given the technological complexities and the high price tags of the task, the two space agencies eventually may pool their efforts and resources to launch one joint mission rather than two competing observatories.

While the launches of Terrestrial Planet Finder and Darwin are likely at least a decade — and a number of technological milestones — away, several groups of scientists are already working to define exactly what fingerprints of life they should search for. In that monumental undertaking, they are guided by the one known example of a life-bearing planet — Earth.

Sagan's experiment with Galileo provided a reassuring start. The probe's instrument suite detected several telltale signs of a planet teeming with life. Galileo found an atmosphere rich in oxygen that contains higher levels of methane than would be expected from geological activity alone. It also registered traces in the terrestrial spectrum characteristic of the chlorophyll molecule, which plays a key role in the photosynthesis of plants.

More recently, two teams of astronomers repeated Galileo's observations with an interesting twist. One team was led by Wesley Traub of the Harvard-Smithsonian Center for Astrophysics and Neville Woolf of the University of Arizona, the other by Luc Arnold of the Observatoire de Haute Provence and Jean Schneider of the Paris Observatory in France.

Not having a spacecraft far enough away, they took spectra of earthshine — the glow of sunlight reflecting from our planet and falling on the unlit part of the Moon. While Galileo observed only a limited area of Earth's surface, earthshine yields a spectrum integrated over the entire visible face of Earth, a view more akin to what we'd see of a distant alien world. Sure enough, both the American and French teams identified spectral features due to water vapor, oxygen, and ozone.

As Traub points out, these signs of life would have been detectable for significant fractions of Earth's history, much longer than it has harbored intelligent life. Our planet has maintained an oxygen-rich atmosphere for some 2 billion years, and its spectrum has exhibited chlorophyll's traces since the first land plants evolved about 500 million years ago. As Woolf puts it, "Any advanced civilization that cared to inquire would know that life has been present on Earth for a very long time."

Next, their team would like to determine how the spectrum of earthshine changes as different areas of the planet rotate into view, and as cloud cover changes. Eric Ford and Edwin Turner of Princeton University and Sara Seager of the Carnegie Institution of

Ray Jayawardhana *is an associate professor of astronomy at the University of Toronto. He explores the origin and diversity of planetary systems using some of the world's largest telescopes.*

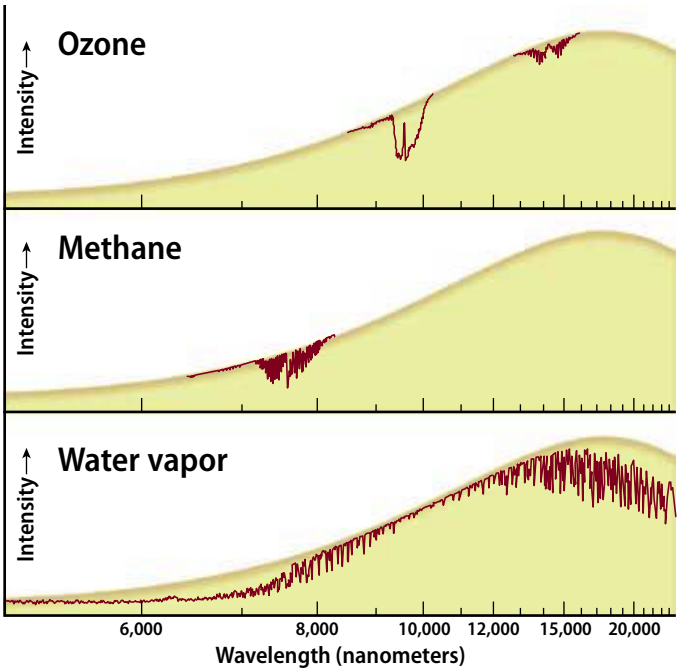
NEPTUNE-SIZE PLANETS — and an associated asteroid belt — have been discovered around the normal star HD 69830. Using ground-based optical telescopes, astronomers have yet to find planets with masses much less than Neptune. ESO

Washington have already calculated models of variations that might be seen as Earth rotates.

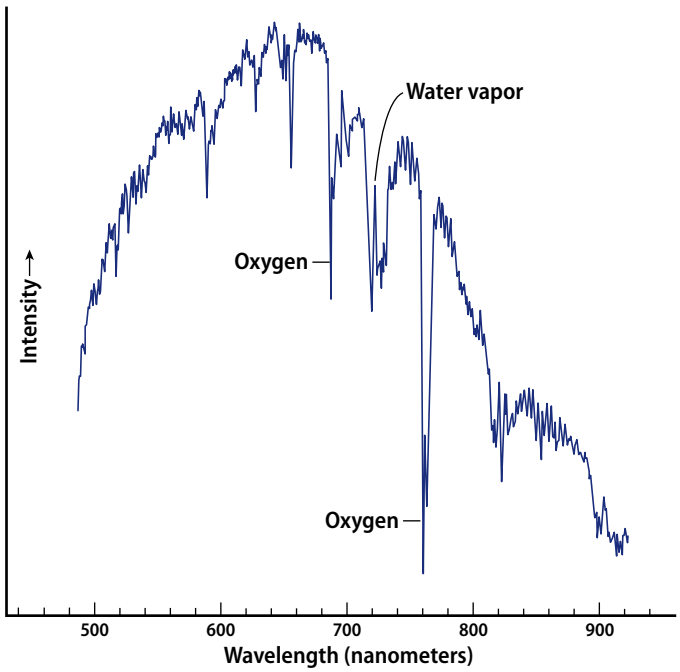
Chemistry tells the tale

These early observations and calculations of life signs are paving the way for serious planning for the Terrestrial Planet Finder and Darwin missions. In 2002, NASA's Jet Propulsion Laboratory (JPL) commissioned a group of scientists, including Traub, Woolf, and Seager, to evaluate the relative significance of various planetary biomarkers and to recommend observing strategies for TPF.

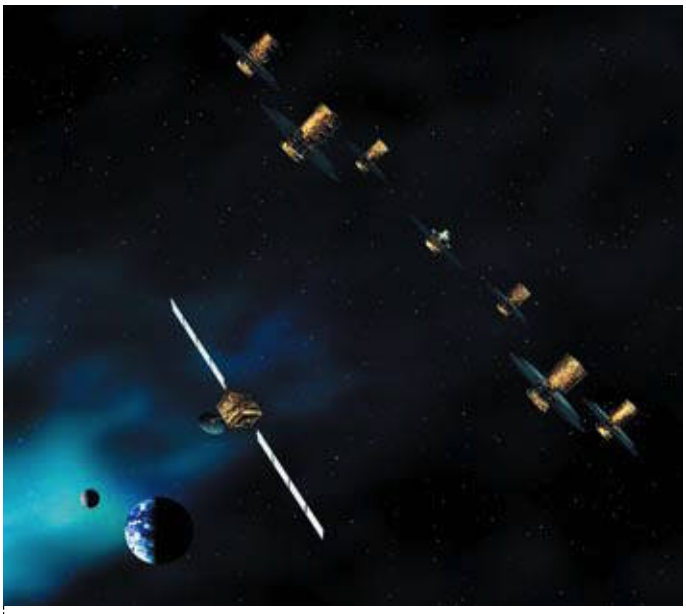
Not surprisingly, among the most reliable biomarkers identified by the TPF study are oxygen molecules (O_2), a byproduct of photosynthesis by plants on Earth, and its cousin, ozone (O_3), which is actually easier to detect in a spectrum even though it is much less abundant. Oxygen molecules do not stay single for long; they combine easily with other compounds, such as silicon in rocks, in a process known as oxidation. "So, to sustain a large amount of oxygen in a planet's atmosphere, there needs to be continuous production," Traub explains. And life as we know it is an excellent source of oxygen.



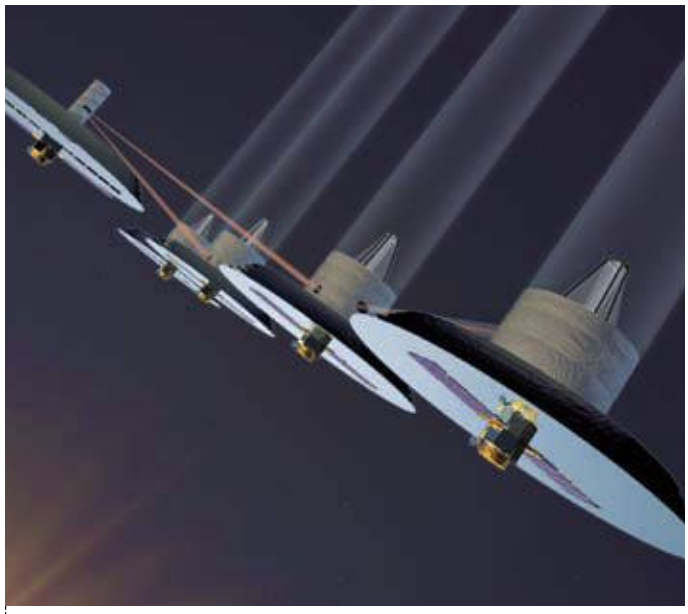
LIFE'S SPECTRAL SIGNATURE will likely consist of a mixture of ozone, methane, and water vapor. The calculated spectra here show what effects these trace gases would have on the thermal spectrum of an alien Earth. W. TRAUB (CfA)



THE SPECTRUM OF EARTHSHINE clearly shows molecular oxygen (the lines near 690 and 760 nanometers) and water vapor (the band between 710 and 730 nanometers) superposed on the solar spectrum. N. WOOLF (UNIVERSITY OF ARIZONA) ET AL.



THE EUROPEAN SPACE AGENCY'S DARWIN MISSION will try to detect the signature of life on other worlds by examining the spectra of distant exoplanets. ESA



NASA'S TERRESTRIAL PLANET FINDER will look for the spectral signature of life with both an infrared interferometer array (above) and a visible-light coronagraph. NASA

Does that mean the detection of oxygen or ozone in a planetary spectrum is a foolproof indication of life? Not necessarily, says James Kasting of Pennsylvania State University, another member of the Terrestrial Planet Finder working group on biomarkers and a renowned expert on planetary atmospheres. "We know of non-biological processes that can also result in an oxygen-rich atmosphere," he points out.

One such example is Venus with its runaway greenhouse effect. The breaking up of water molecules (H_2O), followed by the quick escape of hydrogen into space, continuously replenishes the oxygen in its atmosphere. Another example would be an ice-covered planet massive enough to hold onto its oxygen. The frozen crust would prevent the oxygen from interacting with minerals on the surface, thus retaining it in the atmosphere.

Although scientists need to guard against such false positives, the identification of either oxygen or ozone in an exoplanet spectrum would be "very exciting and significant," as the Terrestrial Planet Finder biomarker report concludes.

SEARCHING FOR LIFE: A FASTER, CHEAPER ALTERNATIVE

Detecting life on an extrasolar Earth will probably have to await the launch of Darwin or the Terrestrial Planet Finder spacecraft a decade or more from now. But if we are lucky, there's a chance of doing it much sooner and more cheaply, says Michael Jura of the University of California, Los Angeles. In fact, current ground-based telescopes are already up to the task, provided many other "ifs" are satisfied.

When a Jupiter-like planet passes in front of a Sun-like star, as seen from Earth, it covers about 1 percent of the star and causes an equivalent dip in brightness. As of June 2006, ten such transits of extrasolar planets have already been observed.

But what if the parent star were much less massive than the Sun, say a tenth of a solar mass? Such a star, called a late-M dwarf, has a diameter about as small as Jupiter. If such a star harbors a Jupiter-like planet in a tight orbit that happens to be seen edge-on from Earth, we might see the host star undergo a total eclipse, Jura points out.

What's more, if the hypothetical system also included a second planet, then its feeble reflected light might peek through during the total eclipse. "That would give us a chance to measure its colors in order to look for signatures of life," says Jura, who is well regarded among his colleagues for thinking outside the box. Of course, as Jura himself concedes, the chances of all the conditions being just right are rather small. To begin with, astronomers do not know how common — or rare — it is for low-mass stars to harbor close-in Jupiters. Current planet searches using radial-velocity measurements have concentrated on Sun-like stars, rather than their punier cousins.

That's partly due to an Earth-centric bias, but also because stars with a lower mass are significantly fainter, making precise spectral observations more difficult. A new radial-velocity survey specifically targeting low-mass stars could provide the first clue. Paul Butler of the Carnegie Institution of Washington, Geoffrey Marcy of the University of California, Berkeley, and Fred Adams of the University of Michigan are using the 6.5-meter Magellan Telescope in Las Campanas, Chile, to survey 100 M-type dwarfs in search of jovian planets. It's also possible that one of more than 20 ongoing planet-transit searches around the world will turn up a near-total eclipse of a low-mass star.

For now, Jura guesses that perhaps only one out of every 100,000 low-mass stars would experience a total eclipse by a close-in giant planet. Cataloging and monitoring that many low-mass stars in search of an eclipsing Jupiter with a terrestrial sister is far from a simple task.

"While the odds of success are highly uncertain and the observations are technically challenging, at least we don't need to wait a decade to start the search for extrasolar life," Jura argues. — *R. J.*

LIFE-BEARING EXOPLANETS are most likely to form around stars with a mass not too different from the Sun's. Although a terrestrial planet could condense out of debris left over from the formation of a high-mass star, such a star would die before life could arise. And worlds born around a low-mass star would need to orbit too close to the star for a stable climate to develop. *ASTRONOMY:* TOM FORD

Chris Chyba, a planetary scientist at the SETI Institute in Mountain View, California, believes that unambiguous detection of life via remote sensing will be extremely difficult. Separating true biomarkers from those that could also arise from non-biological processes is far from trivial, he thinks, especially if scientists have little information about the planet's surface conditions. "But that doesn't mean we shouldn't be trying to do it," says Chyba.

Perhaps the most convincing evidence for life on a distant world would be finding multiple biomarkers. One possibility would be to detect oxygen or ozone along with liquid water, coupled with high levels of carbon dioxide, exhaled by animals, or methane, which is released on Earth by anaerobic bacteria in rice paddies, peat bogs, and tundra. "The general consensus is that if we find several of these biomarkers simultaneously, it will be a very strong indicator of life's presence," says Malcolm Fridlund, Darwin project scientist at ESA. Of course, finding those signatures would not distinguish between primitive bacteria and complex aliens. That would require a different kind of sign.

TO EXPLORE THE TEMPERATURE RANGE at which life might exist, "We'll model everything from frozen hells to burning hells." — *Vikki Meadows*

Alien Earths — with a twist

Some scientists worry that life elsewhere would be so fundamentally different that biomarkers identified for terrestrial life might be all but meaningless. Traub agrees that "There's great danger in generalizing from one example." On the other hand, he argues, life anywhere may have at least a few things in common. "Despite all our speculations, we haven't come up with a convincing alternative to water and carbon chemistry as a basis for life. So I see no reason to go looking for more exotic things, at least for now," he explains.

Of course, there could well be many forms of life that would not register on a planet's overall spectrum, such as bacteria underground or in deep ocean vents. And it may be difficult to detect biomarkers at the surface — like chlorophyll on Earth — if much of the planet were covered by clouds.

Coming up with life-bearing worlds different from the present-day Earth is one of the goals of the Virtual Planetary Laboratory, a NASA-funded multimillion dollar project led by JPL's Vikki Meadows. Her team consists of 28 researchers from disciplines as varied as statistics and biochemistry. They are developing sophisticated computer simulations of the environments and spectra of a broad range of rocky planets with, and without, living organisms. "We are modeling life as we know it — but not necessarily in the balance we have here on Earth," she says.

Meadows' plan is ambitious: to construct the first models of terrestrial planets that combine the effects of — and the interplay between — stellar heat, climate, chemistry, geology, and biology. Once those models are in place, she and her colleagues first plan to compare them with Venus, Earth, and Mars. Later, they will reconstruct what the early Earth would have looked like from a distance, before its atmosphere became rich in oxygen. Eventually, the researchers plan to "play around with the recipe," trying different combinations of size, composition, and temperature to investigate the effects on life and vice versa. To explore the range of temperatures at which life might exist, for example, "We'll model everything from frozen hells to burning hells," says Meadows.

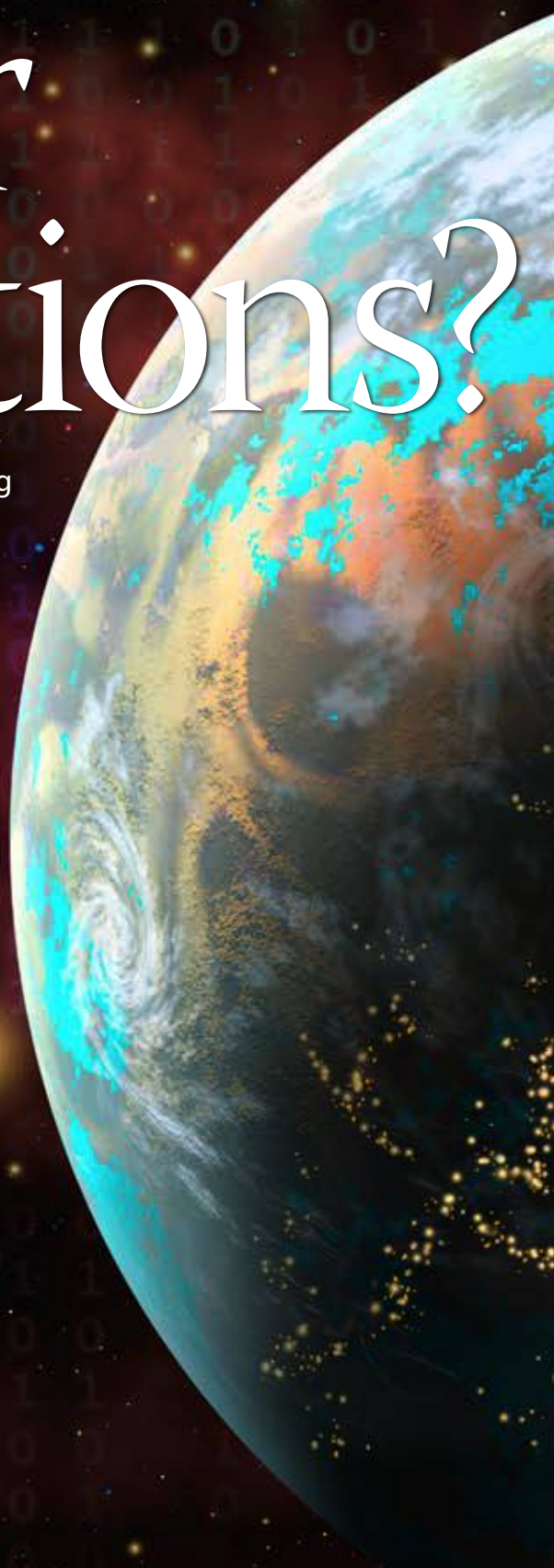
That's all part of the homework scientists need to complete in preparation for the day when we are able to catch the faint glow of a distant world and decipher its signs of life. When that day comes, chances are that we will see our own planet — and ourselves — in a whole new light.

Will we find other civilizations?

As technology improves, so do our chances of detecting a signal from extraterrestrials. /// BY SETH SHOSTAK

The search for extraterrestrial intelligence (SETI) keeps progressing nicely, but at a tempo that's sometimes hard to measure. Yes, the data rates at today's SETI telescopes would choke a hippo, and sure, new hardware and software are able to comb through a hundred million channels of cosmic static faster than you can say "Jodie Foster." But the bottom line remains the same: still no confirmed signal from any other world.

In light of this failure to find aliens, some pundits urge us to rein in our expectations. They caution that SETI should be viewed as a "project for the generations." Could this be true? After all, SETI has carefully investigated only a tiny volume of the galactic bailiwick. At today's rate of scrutiny, it will take centuries or even millennia to check for faint signals from as much as 1 percent of the Milky Way's star systems.



AN INHABITED PLANET elsewhere in our galaxy might appear different than Earth. In this painting, an advanced civilization resides on the earthlike planet in the background. To search the sky for other life, beings have constructed a huge radio telescope on the far side of their moon. LYNETTE COOK FOR *ASTRONOMY*

But today's rate of scrutiny is just that — today's rate. In fact, the technology used to hunt for signals is improving exponentially. SETI's on a roll, and the time scale for finding an alien signal could be shorter than anyone can imagine.

Also, the great appeal of the search continues to stoke the imagination of scientists around the world. During the past few years, a gush of new ideas about both the technology and the sociology of SETI has burst on the scene.

Listening with new technology

It's been more than 4 decades since Frank Drake first swung an 85-foot-diameter radio telescope in the direction of Tau Ceti and Epsilon Eridani (two Sun-like stars within a dozen light-years of Earth). He was hoping to find signals broadcast by alien neighbors. Drake tuned his receiver to the microwave band at 1,420 megahertz (MHz), equivalent to a wavelength of 21 centimeters.

The majority of today's SETI practitioners do the same. 21cm is special because cold, interstellar hydrogen gas radiates at this wavelength. Once radio astronomers realized this, they were able to map most of the Milky Way Galaxy by plotting the positions of vast hydrogen clouds.

THE VERY LARGE ARRAY (VLA) is a collection of 27 radio antennae located at the National Radio Astronomy Observatory site in Socorro, New Mexico. Each antenna in the array measures 82 feet (25 meters) in diameter and weighs about 230 tons. The Y-shaped array can be arranged into 4 different configurations, depending on the distance between each of the antennae. NRAO/AUI

A new breed

The perennial difficulty with speeding up SETI has been the lack of a large, dedicated radio telescope optimized for a systematic hunt. That hole is about to be plugged. The SETI Institute and the Radio Astronomy Lab at the University of California at Berkeley are building a new instrument that will accelerate enormously the examination of individual star systems.

Christened the Allen Telescope Array (ATA) in appreciation of generous funding provided by Paul G. Allen (cofounder of Microsoft), this instrument departs from the usual radio-telescope design. Instead of a massive, single reflector (*à la* Arecibo in Puerto Rico), or a small array of relatively large telescopes (*à la* the Very Large Array in New Mexico), the Allen Telescope Array will sport hundreds of dishes, each with reflectors 20 feet in diameter.

The ATA is being constructed at Berkeley's Hat Creek Radio Observatory, located on ranch land in the Cascade Mountains about 250 miles northeast of San Francisco. According to Leo Blitz, the Radio Astronomy Lab's director, "This is probably the best spot in the country to put the array. The population density is low, and consequently, so is the level of radio interference."

The first group of 42 ATA antennae already have been planted, outfitted, and checked. Eventually, 350 antennae will spread irregularly throughout a circle about two-thirds of a mile in diameter.

So what can the ATA do that existing telescopes cannot? To begin with, the array will cover a wide sweep of the radio band, from 500 to 11,200 MHz — all at the same time. Second, those small, individual dishes will provide a broad field of view, 2.5° at 21cm wavelength (the VLA's field of view is 0.6°). Third, an array with hundreds of antennae will produce radio pictures with exceptional dynamic range; strong radio sources will reveal their faintest features.

THE ROBERT C. BYRD Green Bank Telescope (GBT) in Green Bank, West Virginia, is the world's largest fully steerable radio telescope. The GBT stands 485 feet (148 meters) tall. Its dish measures 330 by 360 feet (100 by 110 meters). NRAO/AUI

Some of the research areas where the ATA will excel include mapping the neutral hydrogen in galaxies out to almost 900 million light-years, detecting gravitational waves, and finding slowly rotating pulsars. Mapping galaxies and sniffing out pulsars are straightforward, but you might wonder how a radio telescope could ever be used to detect gravity waves.

Keep in mind that gravity warps space. Then imagine that deep in the chaotic innards of a distant galaxy, two massive black holes are approaching one another slowly, the consequence of galactic cannibalism. Such processes flood the universe

with enormous gravitational swells, and the resulting space warp slightly changes the times that pulsar signals arrive. With its ability to measure these changes to a precision better than a millionth of a second, the ATA can gauge the subtle ebb and flow of gravity waves caused by cataclysmic events in the far-off cosmos.

Without doubt, the ATA will help SETI do a better job. But the ATA is not the only system with which such reconnaissance will be accelerated. Australian engineers have built a multiple-receiver feed to affix to the Arecibo telescope. This new compound radio eyeball, nicknamed ALFA (Arecibo L-Band Feed Array), is gazing at seven closely spaced spots on the sky simultaneously.

According to Dan Werthimer, director of the Berkeley SETI Program, "With this new hardware, we'll be doing a systematic survey. To take advantage of ALFA, we're building a new receiver: the SERENDIP V spectrometer. Actually, it's seven spectrometers, one per feed. Each will individually cover 3 times more than our current equipment." In addition to SETI research, ALFA has been scanning the sky for pulsars, supernovae, black holes, and planets.

The Berkeley team has also upgraded the popular (and free) SETI@home screen saver, employed by millions of computer users to help hunt for extraterrestrial signals. The upgrade has increased the total bandwidth of the data available for SETI@home, and Werthimer's thinking about doing the same for a Down-Under experiment — Southern SERENDIP — so home computers can pore through the cosmic bits and bytes collected by Australia's Parkes radio telescope.

Seth Shostak *is senior astronomer for the SETI Institute in Mountain View, California.*

THE ARECIBO RADIO TELESCOPE, located in Puerto Rico, is the world's largest. Unlike many smaller radio telescopes, the Arecibo installation cannot be pointed to a particular spot in the sky. The telescope is stationary, and the sky rotates above it. NRAO

Optical SETI

Radio SETI is on the brink of a major spurt in speed. As it turns out, so is the other popular SETI technique: looking for very brief pulses of light aimed our way by extraterrestrials deliberately trying to get our attention.

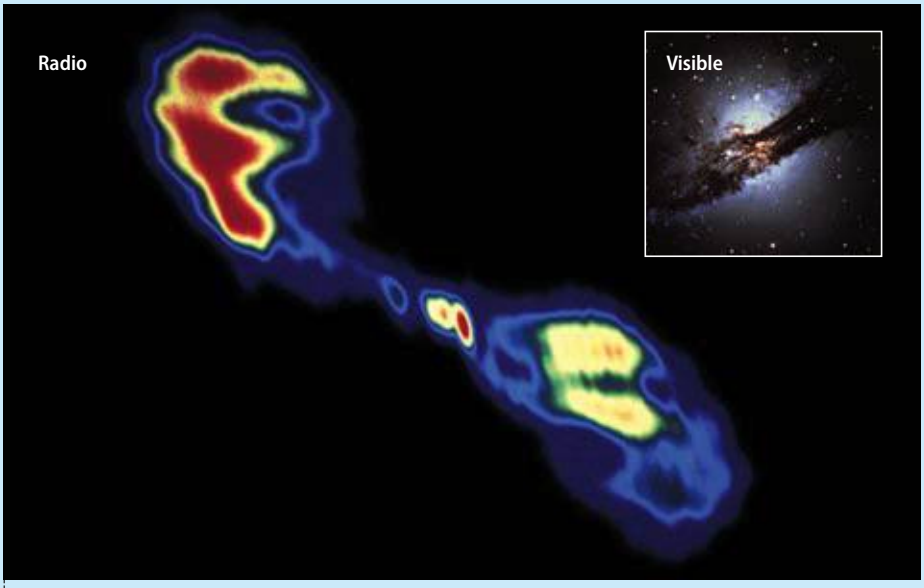
The idea of using visible light as a signaling device is an old one. Even 19th-century scientists considered building mirrors and lanterns to establish connections with clever creatures supposedly residing on the Moon or Mars. More recently, the development of high-powered lasers, able to produce blindingly intense light pulses for a billionth of a second, has revived this idea. If such a laser were coupled to a telescope mirror, it would be capable of pouring into someone else's solar

system more photons than our Sun does — at least during the nanosecond flash.

Clearly, if we have technology sufficient for interstellar light communication, then so should advanced aliens. All that may be required to detect the extraterrestrials in this way is to connect high-speed photomultipliers to our telescopes and scan for far-off flashes.

One of the difficulties with such a search is that the photomultipliers frequently "light up" with pulses that could be extraterrestrial in origin but most likely are just cosmic rays, radioactive decays, and other instrumental effects. The optical SETI experiment at Lick Observatory, which is a collaborative effort with the SETI Institute and Berkeley's Space Sciences Lab, uses three photomultipliers in parallel to reduce the number of false alarms drastically.

At Harvard University, Paul Horowitz and his team have concocted a different scheme for eliminating false alarms. They've inspired an enthusiastic team of faculty and volunteers at Princeton University to renovate a mothballed 36-inch telescope to help sort out which signals are real. If a burst of photons from an alien broadcaster lands in the Harvard telescope, then the instrument at Princeton, which is about 300 miles away, should light up roughly a millisecond earlier or later, depending on the transmitter's sky position. That slight difference in arrival time is measured easily, and it is a gold-plated guarantee that the signal really comes from deep space.



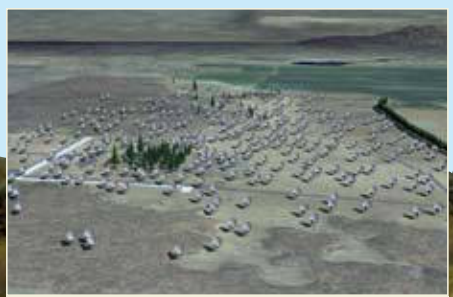
CENTAURUS A (NGC 5128) ranks among the sky's strongest radio sources. Most of this galaxy's radio emission comes from two huge regions on opposite sides of the object's center. ***Inset:*** **A mammoth dust lane mars Centaurus A's visual look.** NRAO/AUI; INSET: NOAO/AURA/NSF

While optical SETI has, until now, restricted its gaze to individual star systems, wholesale stellar scrutiny is coming soon. Horowitz's team has built a telescope whose sole purpose is to scan the entire universe visible from Massachusetts. This sky-survey instrument has a 72-inch mirror and a detector able to image a patch of celestial real estate somewhat larger than the Full Moon. First light came April 11, 2006, and the new telescope has started sweeping the sky. In about a year's time, the survey will have covered the whole sky, dwelling for roughly a minute on any particular patch.

When will we know?

Even aside from the new ideas that continually enrich SETI, one thing's for sure: The pace of exploration is accelerating. Any quantitative measure of search speed (for example, the number of simultaneous channels SETI radio receivers can monitor) shows an exponential increase since Drake's 1960 experiment. Indeed, search speed has been following a growth curve known in the computer industry as Moore's Law. This rule of thumb, first enunciated by Silicon Valley pioneer Gordon

THE ALLEN TELESCOPE ARRAY (ATA) will provide new insights into star formation, the density of the early universe, magnetic fields in the interstellar medium, and a host of other applications. At the same time, this 21st-century radio telescope will search for possible signals from advanced civilizations in our galaxy. This image shows the ATA's first three installed dishes. SETI INSTITUTE

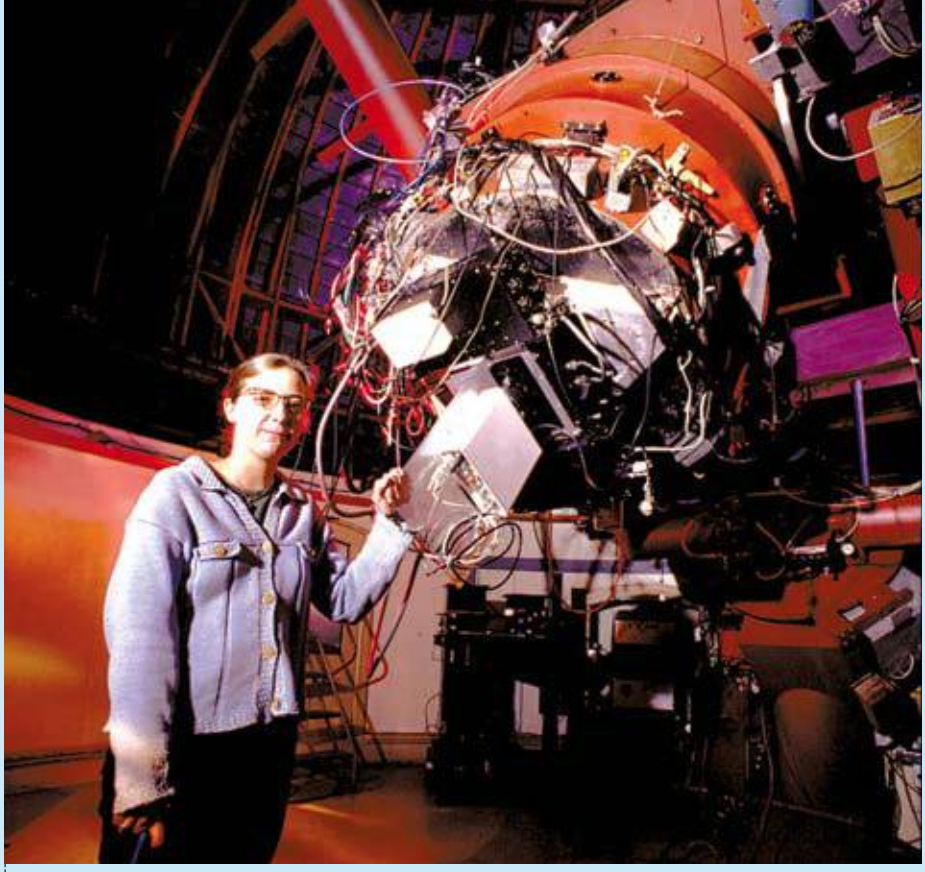


WHEN FINISHED, the ATA will comprise 350 radio antennae. SETI INSTITUTE

Moore, states that computing power per dollar doubles every 18 months. There's no mystery in the fact that radio SETI, at least, follows this law closely: After all, much of SETI's improvement is linked directly to computational power.

In other words, the speed of scrutiny, at least for facilities like the ATA, is somewhat predictable. So if we knew how many galactic civilizations were broadcasting detectable signals, we could add this to the known rate of improvement in search technology to make an estimate of when SETI will find what it's looking for.

How many star systems in our galaxy host intelligent beings with transmitters switched on? The number reckoned by the experts ranges widely: Carl Sagan thought there might be a million or more broadcasting civilizations in the Milky Way. Isaac Asimov figured a half-million. Frank Drake is more conservative: 10,000.



THE OPTICAL SETI PROGRAM is conducted, in part, at Lick Observatory in Santa Cruz, California. Here, University of California graduate student Shelley Wright poses next to the 1-meter Nickel Telescope used to conduct the search. SETI INSTITUTE

No time like the present

Even if the lowest of these numbers is correct, and only one in a few tens of millions of stars hosts a technological society, instruments such as the ATA may find something relatively soon. In part, this would be a consequence of improved astronomy. Recent results by researchers hunting for extrasolar planets suggest stars with higher heavy-element content are more likely to sport orbiting worlds. This type of information will allow us to refine our selection of SETI targets, as will new programs sponsored by NASA's Astrobiology Institute to investigate the habitability of planets around dwarf stars — the most common stellar systems.

Even better target selection will be possible if future space-based telescopes such as NASA's Terrestrial Planet Finder and the European Space Agency's Darwin find planets whose atmospheres contain oxygen and methane — telltale markers of biology. Of course, just finding worlds with life doesn't imply intelligence (during 99.9 percent of life's history on Earth, none of it was smart enough to build radio transmitters). But if, 2 decades hence, we have a long list of planets bursting with biology, that would be a tremendously helpful resource for our search for intelligent life.

Even assuming only modest improvements in our ability to narrow our search, I reckon we will have examined enough stellar habitats by the year 2025 to discover an alien transmitter. To arrive at this date, I am taking Frank Drake's relatively conservative estimate of the galactic population of sentient beings.

Of course, some researchers think that even Drake's estimate is far too high. If so, my prediction that we will detect an alien signal within the next 20 years is optimistic. Only events will prove whether I'm right or wrong, but the bottom line is both simple and encouraging. The search for extraterrestrial intelligence is surfing a thunderous wave: Both the SETI experiments and the hardware are getting better at an ever-increasing rate. Finding a signal that indicates life elsewhere may be something not for the next generation, but for ours. A

Quest *for a* living

How do you search for extraterrestrial life when you don't know what it will look like?

/// BY ALAN LONGSTAFF

Will we recognize alien life if we stumble across it?

Maybe not. It's highly unlikely, after all, that the cameras of our space probes will capture images of planetary surfaces covered with organisms or the artifacts of intelligent life-forms.

Chances are the evidence will be much more subtle: tantalizing spectral lines of biomolecules in the light from a distant earth-like world, or structures within rocks from another planet that are not of obvious geological (or even biological) origin. When we discover any such evidence — actually, long before we reach that point — we're going to need a working definition of what life is and how we'll recognize it.

Astrobiologists argue some properties must be universal to life wherever it occurs. First, life is a complex chemical system able to replicate itself and undergo evolution. Those organisms best-suited to their surroundings survive in larger numbers to reproduce, and this process drives the change and diversity so characteristic of life on Earth.

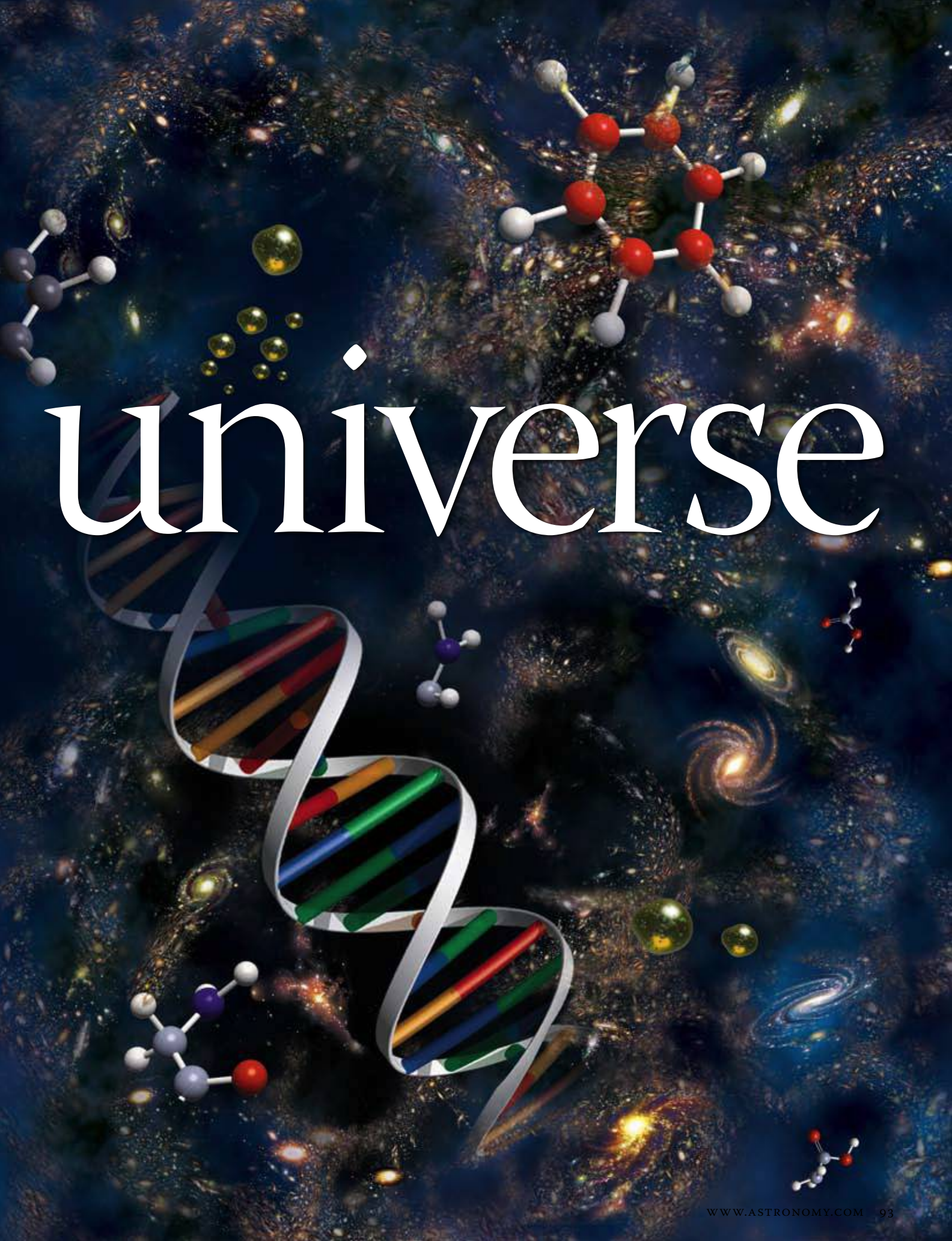
Second, all known life is carbon-based. No other chemical element gets remotely close to carbon for the variety of its chemical interactions, a flexibility that is crucial for living systems.

Third, life almost certainly will need liquid water. Biochemistry is about molecules colliding with each other in the right way and at the right speed, and this requires a liquid solvent. Water happens to be about the best solvent around, although not the only one. It remains liquid over a wide temperature range, and, best of all, there's lots of it everywhere — even, for example, in the star-forming regions of the Orion Nebula.

How common life is in the universe depends on the number of stars with planetary systems, the fraction with habitable planets, and how easily life gets started. Astrobiologists are refining their estimates of these factors.

More than 200 extrasolar planets have been found orbiting some 160 stars. Most are gas-giant planets orbiting close to their parent stars ("hot Jupiters") or in highly eccentric orbits. The hot Jupiters are thought to form a long way from their stars and migrate in. Planetary scientists run computer simulations that show hot Jupiters form and migrate early in the development of planetary systems. If a growing planetary system retains enough dust for the much slower building of terrestrial planets, then

FINDING ALIEN LIFE would easily count as the greatest scientific discovery ever. Scientists have only one example — Earth — to go on, but even here, life is tenacious, occupies every available environment, and can survive under astonishing conditions — from deep-sea vents to acidic pools. *ASTRONOMY:* ROEN KELLY


universe

about half the known extrasolar systems could form Earth-mass planets in their habitable zones.

Gas giants in highly eccentric orbits usually eject terrestrial planets from the system. Even so, computer studies show a third of known extrasolar systems able to make Earth-mass planets in habitable zones keep them. Some simulations produce planetary systems that resemble our solar system — but only when the gas giants remain in stable orbits far beyond the habitable zone.

The only measure of how easy it is to make life is to consider the time from Earth's formation, 4.56 billion years ago, to when life originated. The first organisms on Earth left no fossils, so we have to tease out subtle traces of their biochemistry imprinted in the few rocks that remain from those remote times.

The earliest circumstantial evidence for life (gleaned by Stephen Mojzsis of the University of Colorado) is an enrichment of a light isotope of carbon (C^{12}) in metamorphosed sedimentary rocks from West Greenland that are 3.85 billion years old. If we take this at face value, then life got started on Earth rapidly. And if life originated on Earth as soon as conditions allowed, it suggests life is common in the universe.

Inferno

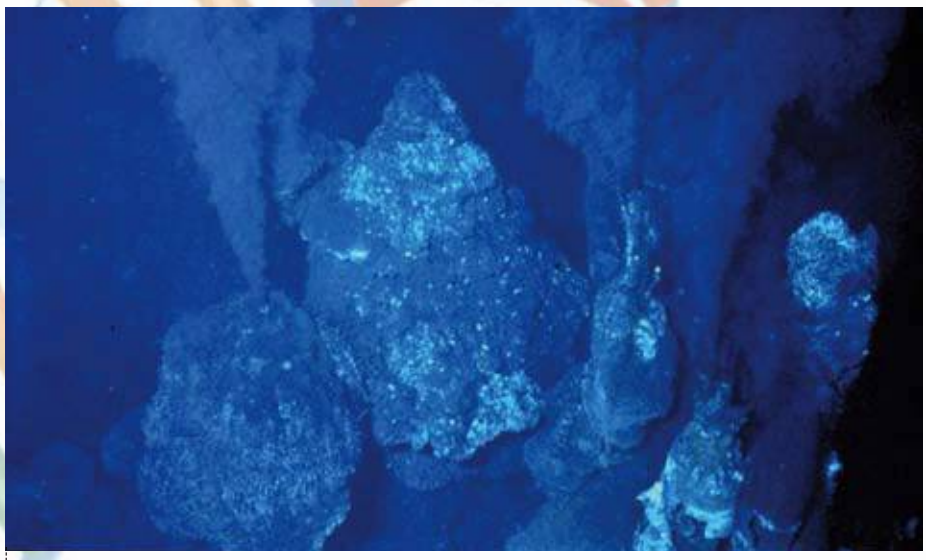
Early Earth was a hellish place. Around 3.85 billion years ago, the massive meteorite impacts that marked the end of planet building had barely ceased. Oceans at a temperature close to boiling covered most of the surface, and the atmosphere, outgassed in just a million years by awesome levels of volcanism, was largely nitrogen, carbon dioxide, and water. There was no oxygen and, hence, no ozone to provide protection from solar ultraviolet radiation. The ionizing power of this radiation would render any land surface and the top few feet of water uninhabitable.

At first sight, early Earth seems totally inhospitable. But over the past few years, scientists have found microorganisms that live among — indeed require — conditions once thought hostile to life. Among these are hyperthermophiles, organisms that thrive in high-pressure water up to 242° Fahrenheit (117° Celsius) without sunlight or oxygen. These astonishing microbes live in and around hydrothermal vents on the ocean floor where new oceanic crust is forming. There, Earth's hot mantle lies close to the surface. Seawater percolates into the crust, is heated to 660° F (350° C) by hot mantle rock, and erupts as a "black smoker" laden with dissolved gases, such as hydrogen, plus metals.

All oxygen-breathing organisms get the energy they need by "burning" hydrogen derived from organic molecules (foodstuffs such as sugars) in oxygen. Plants and many bacteria go one step back and harness sunlight to make the organic molecules from carbon dioxide through photosynthesis. But hyperthermophiles don't need organic molecules or sunlight. They get energy by odd metabolisms that, for example, burn hydrogen with sulfur or carbon dioxide, with all the ingredients supplied by the black smoker.

All terrestrial organisms contain within their cells molecules of ribonucleic acid (RNA), which has a chemical sequence unique to each species. The more closely related two species are, the more alike their RNA sequences.

By comparing the RNA sequences of a representative number of organisms, scientists can work out a family tree for life on Earth. Astonishingly, this reveals the root and lowest branches of the tree are occupied by hyperthermophiles. Thus, life almost certainly started at high temperature. However, we cannot rule out the possibility that life

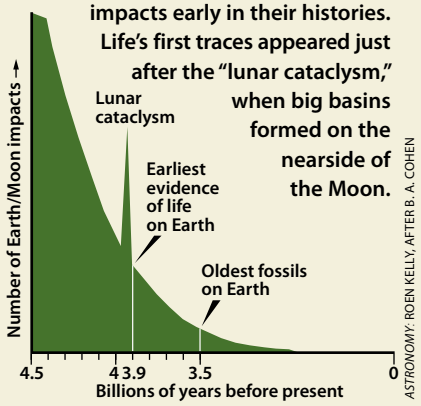


ROBERT EMBLEY, NOAA PACIFIC MARINE ENVIRONMENTAL LABORATORY/MICHAEL PERFIT, UNIV. OF FLORIDA/NOAA VENTS PROGRAM

BLACK SMOKERS — undersea volcanic vents — support entire ecosystems. At the base of the food chain are remarkable heat-loving organisms that glean energy and carbon for life from inorganic materials dissolved in superheated water erupting from the ocean floor. This is life without sunlight or oxygen, and early life may have resembled it.

Lunar cataclysm

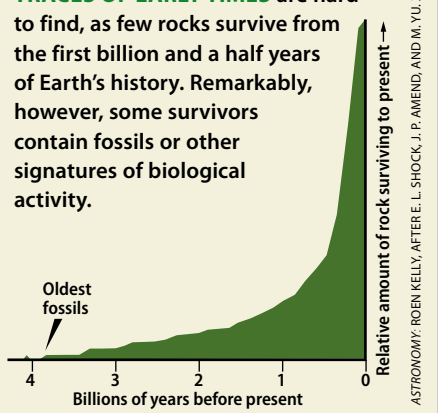
EARTH AND MOON suffered many impacts early in their histories. Life's first traces appeared just after the "lunar cataclysm," when big basins formed on the nearside of the Moon.



ASTRONOMY: ROEN KELLY, AFTER B. A. COHEN

Ancient rocks are rare

TRACES OF EARLY TIMES are hard to find, as few rocks survive from the first billion and a half years of Earth's history. Remarkably, however, some survivors contain fossils or other signatures of biological activity.



ASTRONOMY: ROEN KELLY, AFTER E. L. SHOCK, J. P. AMEND, AND M. YU. ZOLOTOV

Alan Longstaff *started out as a biochemist and now teaches astronomy at the Royal Observatory Greenwich in London.*

APTLY NAMED, *Bacillus infernus* is a hyperthermophile living deep in Earth's crust. This organism breathes iron and manganese dioxide; oxygen poisons it. HENRY ALDRICH, UNIV. OF FLORIDA

started at low temperature (perhaps elsewhere in the solar system) and that hyperthermophiles subsequently evolved. The tree of life shows these were the only traces of early life to survive, with the rest obliterated by the high temperature on early Earth.

Since the early 1990s, many species of viable bacteria, including hyperthermophiles, have been found several miles deep in the warmth of Earth's crust, as predicted years earlier by Thomas Gold of Cornell University. The deep crust may have been the only refuge for early life, affording it protection from the effects of giant impacts that would have boiled away oceans and filled the atmosphere with incandescent rock vapor.

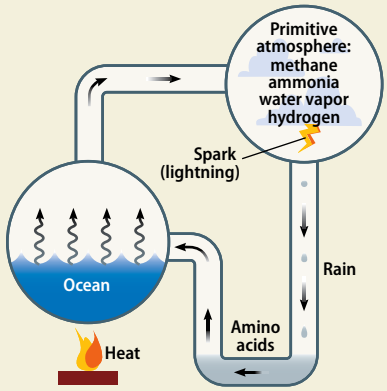
But as the rate of impacts lessened, the temperature of Earth's surface cooled, and oceans began to endure. Thermophile life spread from its deep refuges and evolved into organisms that could survive in the cooler realms nearer the surface, even altering the oceans and atmosphere chemically by liberating oxygen and other by-products. Although we can no longer live together in the same places, we are the descendants of those thermophiles.

On ice

When life emerged from its deep, hot bottleneck, it developed into a larger and more varied biosphere. Terrestrial life's origin and diversification give scientists hope for finding other places where life also could have started. Besides Earth, two locations in the solar system stand out as prime candidates: Europa and Mars. These are two worlds that have — or once had — liquid water as a biological solvent. If we follow the water, we may be able to find life.

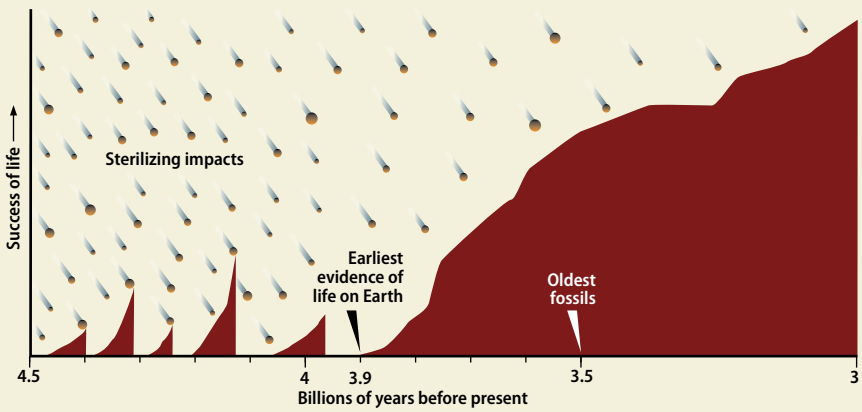
Jupiter's moon Europa teaches us to think laterally. It lies far outside the habitable zone, not receiving enough sunlight to keep water liquid on its surface or to drive photosynthesis. But beneath its icy crust may lie a salty water ocean perhaps 60 miles (100 kilometers) deep. Evidence for this is that a third of Europa's surface resembles pack ice in the Arctic and Antarctic, suggesting it has partially melted and refrozen. Calculations estimate the moon's ice crust is between 5 and 12 miles (8 and 20 km) thick. Tidal tugs from Jupiter and Europa's two flanking

The Miller-Urey experiment



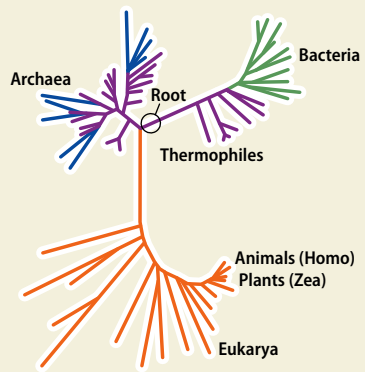
AN ELECTRICAL SPARK, plus water, plus gases thought to match Earth's first atmosphere (methane, ammonia, and hydrogen) created prebiotic amino acids in an experiment by Stanley Miller and Harold Urey in 1953. However, scientists now think the early atmosphere held primarily carbon dioxide and nitrogen, and the energy for creating life came more from chemical and geothermal sources. *ASTRONOMY*: ROEN KELLY

How many times did life begin afresh?



DID LIFE HAVE MORE THAN ONE GENESIS? Impacts big enough to sterilize Earth occurred often during the planet's earliest days. If life began in that violent era, it probably started several times and was wiped out again and again. Scientists speculate the final planet-sterilizing impact happened around 3.9 billion years ago, and all of today's life is descended from a common ancestor that appeared after that event. *ASTRONOMY*: ROEN KELLY, AFTER J. W. SCHOPF

Life's family tree



THE TREE OF LIFE has three major branches, and each evolved from organisms that liked it hot. All life today is descended from thermophile organisms that could survive intense heat. *ASTRONOMY*: ROEN KELLY, AFTER E. L. SHOCK, J. P. AMEND, AND M. YU. ZOLOTOV

MARS: WARM AND WET?

Several findings are hard to reconcile with the idea of a warm and wet early Mars. Water dissolves carbon dioxide in the atmosphere and normally would combine with surface materials to form carbonate rock, such as limestone. Although trace amounts of carbonates have been identified at the surface, Mars shows nothing like the expected amount.

However, discoveries on Meridiani Planum by the Mars rover Opportunity show that the surface water there would have been acidic. In this situation, carbonates would not be deposited.

The mineral olivine, present in basalt rocks, is converted by water to serpentine in just tens of years. Yet surveys by spacecraft find huge areas of exposed, unweathered olivine on Mars. Moreover, planetary scientists find no trace of clays, the final product of water acting on igneous rocks. All this suggests liquid water did not linger at the martian surface.

The mineralogy of Meridiani Planum supports this interpretation. For example, the hydrated mineral jarosite, found by Opportunity, forms when basalt is exposed to acid water under a variety of conditions — but jarosite does not survive prolonged immersion in water.

A simulation of giant impacts, by Teresa Segura and colleagues at the University of Colorado and NASA's Ames Research Center, depicts early Mars as endless winter, briefly punctuated by searing temperatures and scalding rains after large impacts. The impacts heat the atmosphere to more than 900° F (500° C), vaporizing subsurface permafrost. Torrential rainfall and flash floods carve valleys and erode craters. But within a century or so, everything refreezes.

If correct, this scenario offers bleak prospects for life on Mars unless it was protected deep in the crust. — *A. L.*

FLOWING WATER eroded Mangala Valles and many other outflow channels on Mars. But planetary scientists are unsure how long the floods persisted and when they occurred. NASA/JPL

CHAOTIC TERRAIN on Europa resembles pack ice on Earth, providing evidence for an ocean under the moon's ice crust. Measuring shadows cast by the raised ice rafts allows scientists to calculate the thickness of Europa's crust and the dynamic forces changing it. The latter include plumes of warmer ice that cause local melting and resurfacing. NASA/JPL

moons, Io and Ganymede, heat the ocean and keep it liquid.

Although entirely speculative, Europa could have submarine hydrothermal systems like those on Earth where life may have arisen. There is even a mechanism, proposed by Chris Chyba of the SETI Institute and colleagues at Stanford University, to deliver oxygen to the ocean.

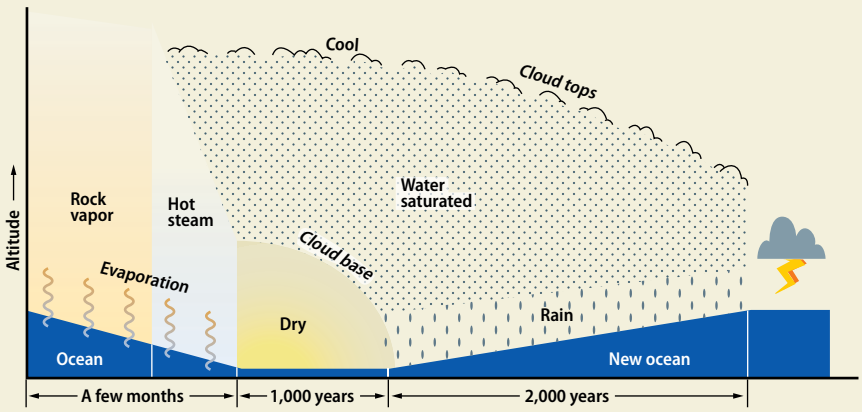
Water ice at the surface of Europa is continually bombarded with charged particles from the Sun and Jupiter that make oxygen as they break up the ice's water molecules. Meteorite impacts churn this oxygen to a depth of about a yard. If the top of Europa's ice crust mixes with the global ocean over millions of years, enough oxygen could reach the ocean to support microscopic life-forms with modest oxygen demands.

Red planet

In all the varied worlds of the solar system, everyone's favorite candidate for exo-life is Mars. The case for past life on Mars is based on the hypothesis that the planet was once warm and wet. Early Mars must have been volcanically active and would have outgassed an atmosphere rich in carbon dioxide and water.

This would be crucial because a substantial greenhouse effect would have been needed to prevent Mars from freezing over, given its distance from the Sun. Unfortunately, Mars lost its global magnetic field about 3.9 billion years ago, when its cooling

What happened when impacts evaporated oceans



HELL ON EARTH followed extremely large impacts, which were common in the planet's early history. Each big impact dumped enough heat into the crust to boil away the oceans while filling the atmosphere with vaporized rock. Eventually, the atmosphere cooled sufficiently to let rain reach the surface, and oceans began to collect. The next big impact started the cycle afresh. *ASTRONOMY:* ROEN KELLY, AFTER K. J. ZAHNLE AND N. H. SLEEP

core stopped generating a field. This let cosmic radiation strip away much of the martian atmosphere, and the temperature plummeted to today's average surface temperature of –60° F (–50° C). Despite this, there is good evidence from NASA's Mars rovers, the European Space Agency's (ESA) Mars Express orbiter, and earlier missions that liquid water once flowed on Mars. Recent data suggest lots of water remains locked up as permafrost in the ground.

If life did start on Mars, one thing is clear: It would not have been at the surface. Mars is bombarded by cosmic and ultraviolet radiation, and its surface rocks are highly oxidizing, making them chemically toxic to life-forms like ours.

What would an underground martian biosphere be like? Microorganisms adapted to the cold seem a reasonable bet, perhaps at the depth where the permafrost melts. This would match the lowest temperature — 0° F (–18° C) — at which terrestrial microbes can grow and reproduce. Perhaps paradoxically, if martian life were deeper in the planet, maybe what survived were thermophiles like those in Earth's crust. Whichever scenario is the case, we will need deep-drilling rigs to find evidence. This appears unlikely in foreseeable robotic missions.

The discovery of methane in the martian atmosphere is highly intriguing. Unless some process is continuously making it, methane won't hang around for more than a few hundred years. Possible sources are volcanic or geothermal activity, a recent comet impact, or life. (Most methane in Earth's atmosphere comes from microorganisms.)

On Mars, the methane tends to concentrate where subsurface water is abundant. This remarkable correlation, while suggestive, needs to be tempered by estimates of the rate of martian methane production. Such estimates show that if the gas is biogenic, the martian biomass can be only around 20 tons. Very small fry indeed.

Are we martians?

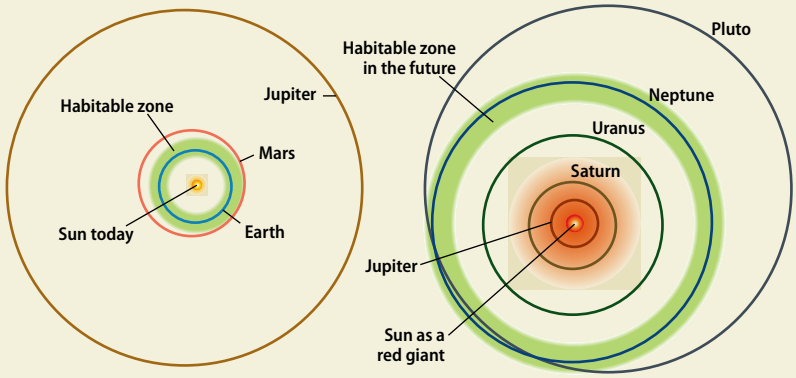
If past or extant life is discovered on Mars, two possible outcomes follow, both profoundly interesting. The first is that Mars life turns out to have a biochemistry obviously like that of Earth. If this proves the case, we can conclude either terrestrial life was derived from Mars or (less likely) terrestrial life infected Mars.

AS THE SUN AGES, ITS HABITABLE ZONE MOVES OUT

Astronomers define a habitable zone as the region of space around a star where a planet can have liquid water on its surface. The zone's location depends on the star — the hotter the star, the farther out the zone will lie (and the wider it will be).

Habitability also depends on a planet's atmosphere. If it contains much heat-trapping greenhouse gas such as carbon dioxide, a planet can remain habitable farther from the star. For life to start and survive, the zone must remain continuously habitable over geological timescales. For this reason, astronomers regard only low-mass main sequence stars as candidates for habitable planets. Sunlike stars have main sequence lifetimes around 10 billion years, and red dwarfs are even longer-lived. More massive stars live too short a time for life to develop very far even if it gets started. And a star of just 3 solar-masses lives for only 500 million years on the main sequence.

But stellar aging adds a complication. As a star evolves, its luminosity generally increases. This drives the habitable zone outward. In extreme cases, the entire zone moves away from its earlier range, condemning any life unlucky enough to emerge on a planet within the formerly habitable zone. In other star systems, including our own, a continuously habitable zone may exist during most of the star's life, even while its inner and outer edges change with the star's brightness. In the Sun's case, for example, the zone that has always been habitable runs from 0.95 astronomical unit (AU) to 1.15 AU. — *A. L.*

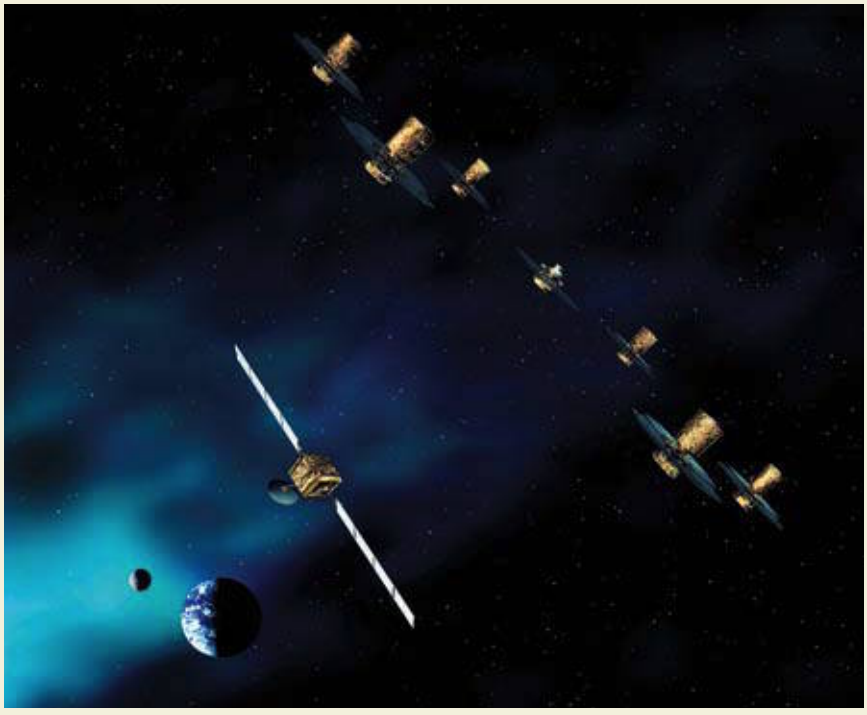


NOTHING is forever. As the Sun ages and becomes a red giant, its habitable zone will move outward — far outward. Earth and the other inner planets will be absorbed and vaporized or simply charred to a cinder, along with any life still living there. Before this scenario unfolds millions of years from now, life will need to find a new home. *ASTRONOMY:* ROEN KELLY

Paul Davies of Maquarie University in Australia has proposed Mars was a better place for life's origin than Earth. Because it has only one-tenth Earth's mass, he argues, Mars would have suffered less bombardment early in its history and would have cooled quicker. This would allow conditions for life to be met earlier on Mars than on Earth. Thirty-two meteorites are known to have come from Mars, so some exchange of rocks between the two planets has occurred.

Calculations by planetary scientists give good reason to believe some microorganisms could survive the impacts at launch and arrival, plus a lengthy journey through interplanetary space, provided they were surrounded by about a yard of rock to shield them from cosmic radiation. Rocks at the edge of an impact can attain escape velocity without undue heating or shock. Terrestrial bacteria have survived acceleration forces of 33,000 Gs and the vacuum and cold of space for more than 2 years, and their spores can spend perhaps millions of years in suspended animation.

The second outcome is that the biochemistry on Mars differs from that on Earth, implying that martian life had a separate genesis. This would be of profound interest in itself and also for its larger implication. That life got going on two planets in the same stellar system would strongly suggest it is abundant in the universe.



ESA'S DARWIN MISSION will survey the nearest several thousand Sun-like stars to search for the chemical signature of life in the light from extrasolar planets. ESA

MISSIONS TO LOOK FOR LIFE

Two missions will launch in the next decade to begin the hunt for habitable planets. Darwin, an ESA mission, will have six 1.5-meter (4.9 feet) telescopes flying in formation, their mutual distances controlled to high precision by laser signals.

Light from a target star will be blocked by a clever trick called nulling interferometry. The technique works by delaying the light slightly in three of the telescopes, forcing it 180° out of phase with respect to the other instruments. This produces destructive interference; the wave crests in one telescope cancel the wave troughs in a second. Light coming from near the star, however, such as from an exoplanet, is less affected and is not suppressed.

NASA's proposed Terrestrial Planet Finder (TPF), which so far has survived the agency's cutbacks, would combine two projects. One closely resembles Darwin, while the other will observe at optical wavelengths. This half of TPF seeks planets using a coronagraph, an instrument that places an opaque disk in the telescope's light path to block the star's direct light so any nearby planets can be detected. — *A. L.*

LIFE TALK

EUROPA
A moon of Jupiter suspected of harboring a salty global ocean beneath an icy crust some 5 to 12 miles (8 to 20 kilometers) thick.

EXTRASOLAR PLANET
A planetary body orbiting a star other than the Sun; also, exoplanet.

HABITABLE ZONE
A region around a star where the physical conditions on planets allow water to remain in a liquid state much of the time.

RNA
Ribonucleic acid; a chemical found in the nucleus and cytoplasm of cells that plays an important role in cellular chemical activities, such as making proteins.

THERMOPHILES
Organisms adapted to life at high temperatures.

Beyond the solar system

We may be able to identify exoplanets that possibly harbor life by telltale signs in their light. Living organisms alter their environments' chemistries. This chemical disequilibrium can show itself as the presence of a molecule that can be explained only if some process is continually regenerating it. For example, our atmosphere contains oxygen only because photosynthesis makes the gas faster than it is lost by processes that consume it, such as the rusting of iron in rocks.

However, chemical disequilibrium does not necessarily indicate life because the imbalance can arise by non-biological processes. Methane on Mars is evidence for chemical disequilibrium, but non-biological explanations can account for it.

Nonetheless, detecting the spectral signature of chemical disequilibrium in the light from an extrasolar planet — namely ozone (a proxy for oxygen), CO_2, H_2O, and methane — would make a case for life. The major problem is that in visible light, the glare of a star outshines its planet 10 billion-fold. Observing in the infrared, where planets radiate most of their energy, reduces the contrast difference by about 1,000 times.

Going to the limit

Although life is far more adaptable than anyone suspected a few decades ago, it still has definite limits. Temperature is arguably the most important. Biochemical reactions cannot happen in a frozen state. This fact imposes a lower bound on the temperature at which growth and reproduction can occur. (Survival in suspended animation, however, is possible at much lower temperatures.) At the other extreme, chemical bonds break and biological molecules fall apart at high temperatures.

The ability of organisms to adapt is also a severe constraint. Having adapted to become fit for one environment (for example, high temperature), an organism has a reduced capacity to diversify into another environment (for example, low temperature). This idea, drawn from evolutionary theory, has been confirmed directly by experiments on bacteria. It implies planets will not be habitable where wide swings in conditions continually occur over short timescales. Organisms can't keep up.

So, in the end, what are life's limits? We don't know precisely, because our experience involves only terrestrial organisms. Yet our single example of biology provides a lever to help us look for life elsewhere in the universe. If there are alien life-forms, they cannot defy thermodynamics or Darwinian evolution. Nevertheless, we should expect to be surprised.

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